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Hao et al.

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(54) **LOW-COST CMOS STRUCTURE WITH DUAL GATE DIELECTRICS AND METHOD OF FORMING THE CMOS STRUCTURE**

(58) **Field of Classification Search**
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H01L 29/42364; H01L 29/105
USPC 257/365, 369
See application file for complete search history.

(71) Applicant: **Texas Instruments Incorporated**,
Dallas, TX (US)

(56) **References Cited**

(72) Inventors: **Pinghai Hao**, Plano, TX (US); **Sameer Pendharkar**, Allen, TX (US); **Amitava Chatterjee**, Plano, TX (US)

U.S. PATENT DOCUMENTS

(73) Assignee: **TEXAS INSTRUMENTS INCORPORATED**, Dallas, TX (US)

2002/0187596	A1 *	12/2002	Yamanaka	.....	H01L 21/2652	438/197
2003/0022434	A1	1/2003	Taniguchi et al.			
2006/0060961	A1 *	3/2006	Lin	.....	H01L 23/3114	257/700
2006/0151840	A1 *	7/2006	Maekawa	.....	H01L 21/823418	257/384
2006/0246716	A1 *	11/2006	Colombo	.....	H01L 21/823857	438/637
2008/0315320	A1 *	12/2008	Cheng	.....	H01L 21/823412	257/379
2009/0108370	A1	4/2009	Tsukamoto			
2010/0203691	A1 *	8/2010	Wu	.....	H01L 21/823814	438/217
2011/0223732	A1 *	9/2011	Griebenow	.....	H01L 21/26513	438/275
2011/0233680	A1 *	9/2011	Hashiura	H01L 21/823412	257/368
2012/0184077	A1 *	7/2012	Bahl	H01L 29/6659	438/268

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Related U.S. Application Data

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* cited by examiner

Primary Examiner — Moazzam Hossain

(74) *Attorney, Agent, or Firm* — Jacqueline J. Garner; Frank D. Cimino

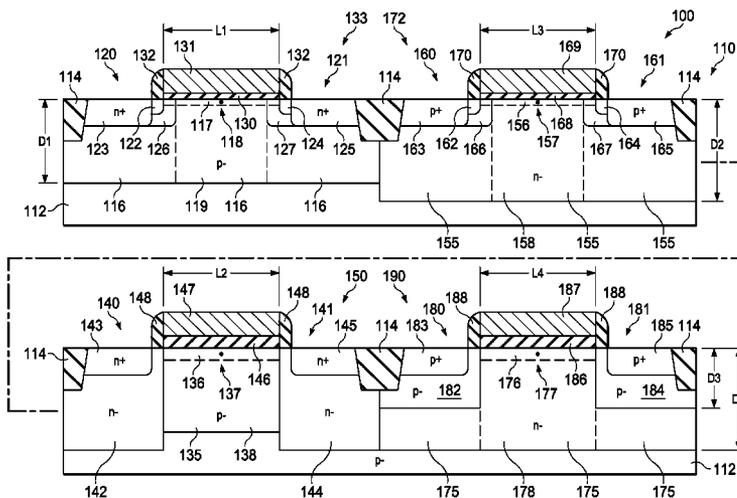
(51) **Int. Cl.**
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H01L 29/423 (2006.01)
H01L 29/10 (2006.01)
H01L 21/8238 (2006.01)
H01L 21/265 (2006.01)

(57) **ABSTRACT**

Impurity atoms of a first type are implanted through a gate and a thin gate dielectric into a channel region that has substantially only the first type of impurity atoms at a middle point of the channel region to increase the average dopant concentration of the first type of impurity atoms in the channel region to adjust the threshold voltage of a transistor.

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5 Claims, 24 Drawing Sheets



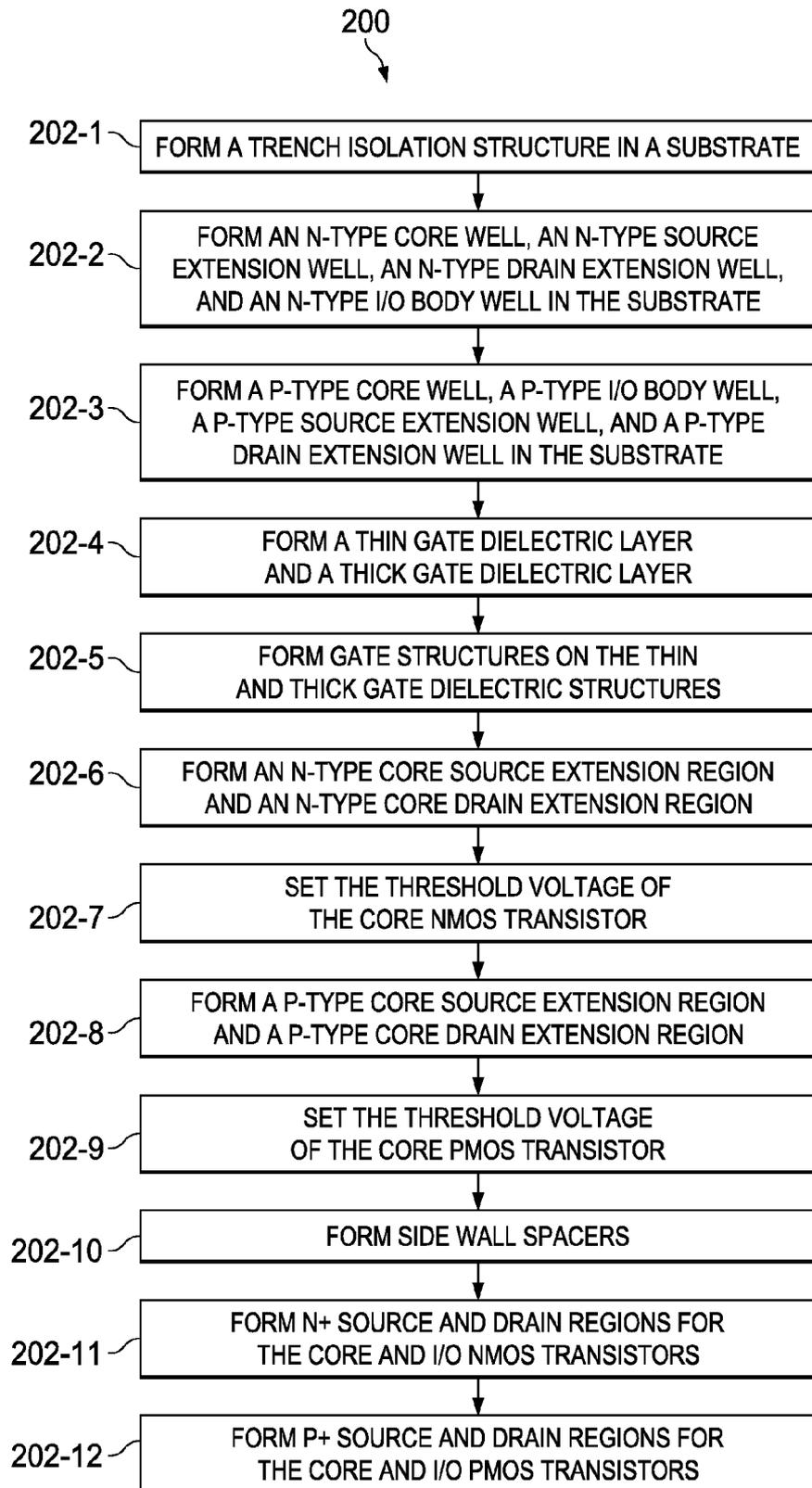


FIG. 2A

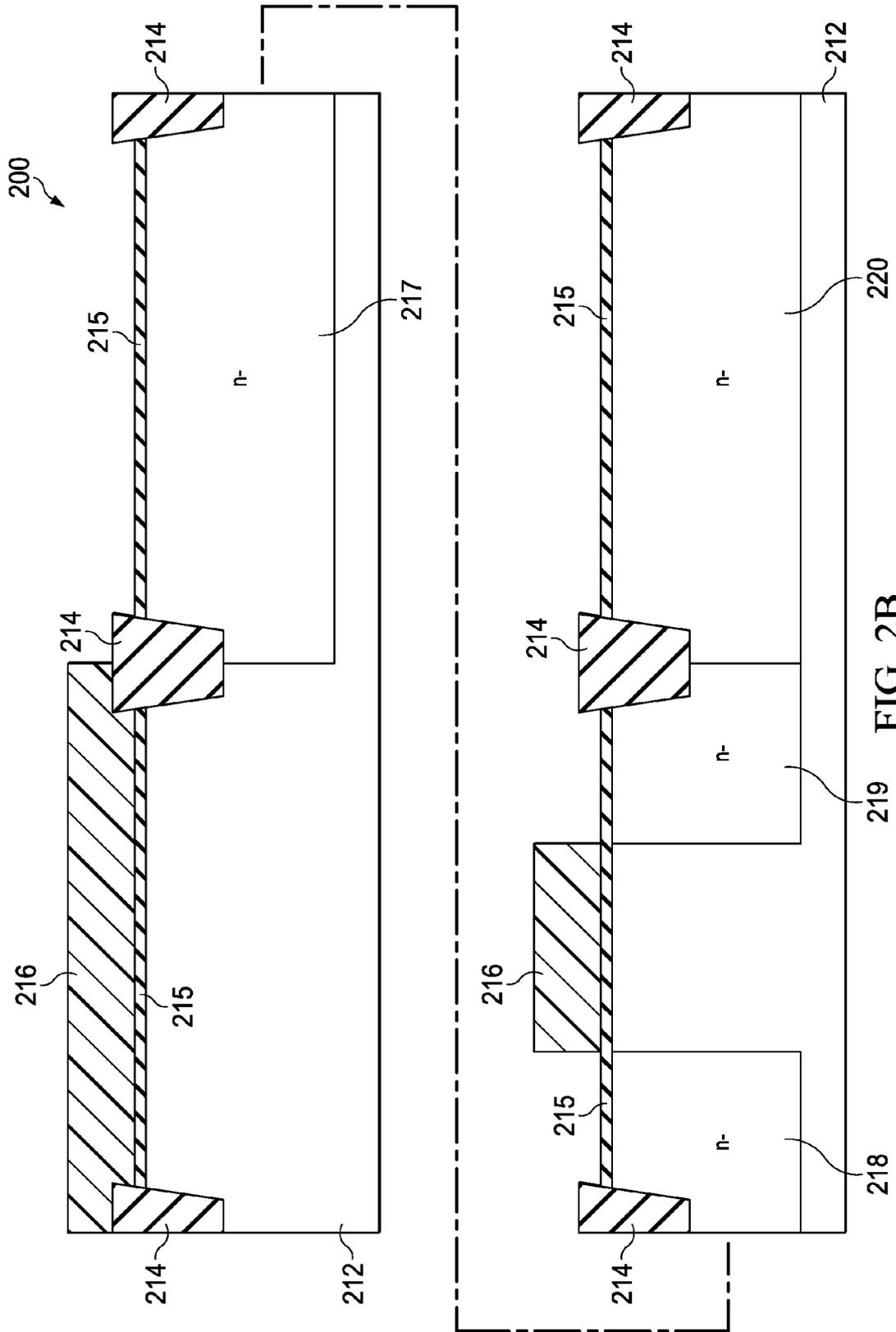


FIG. 2B

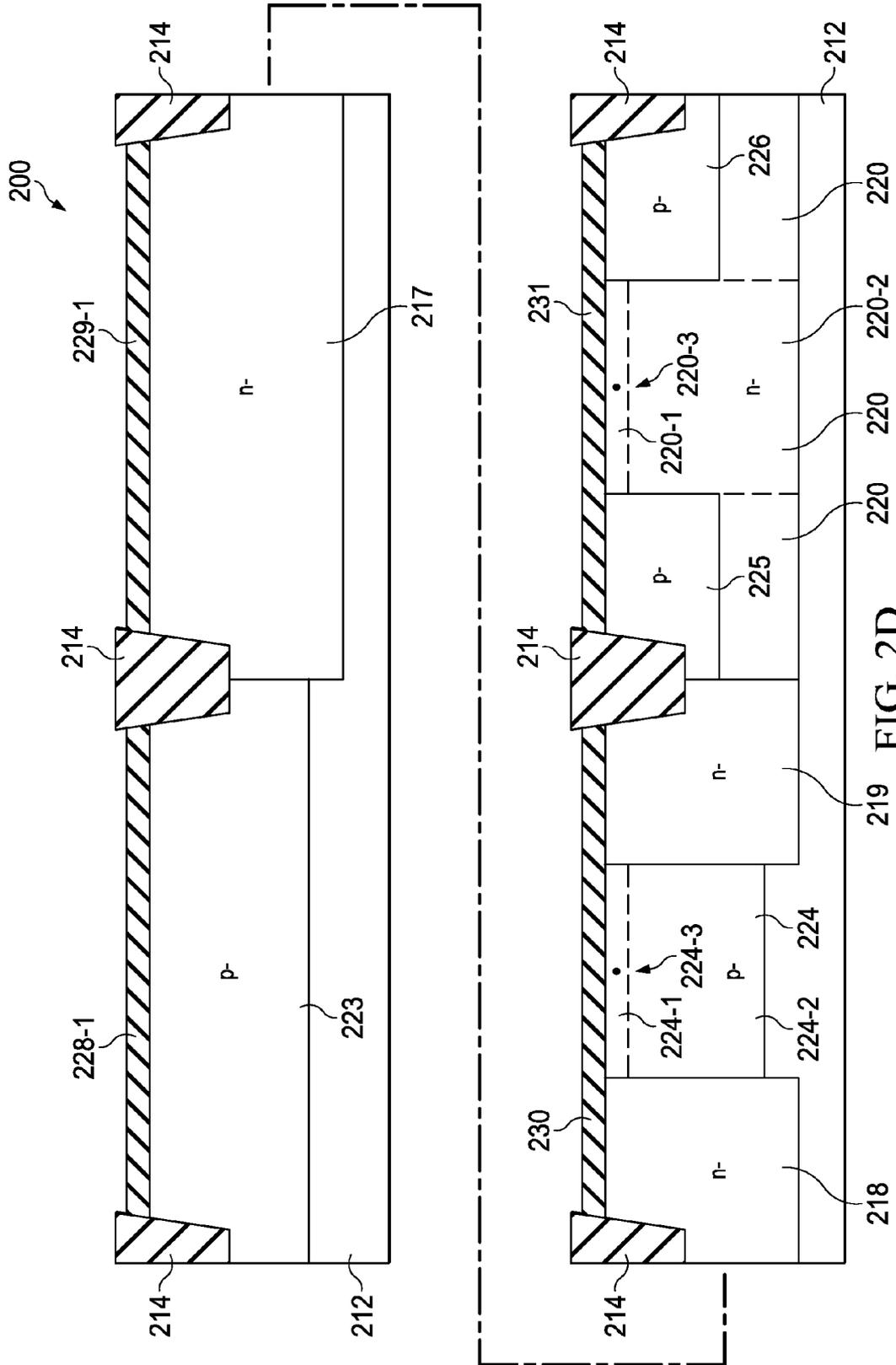


FIG. 2D

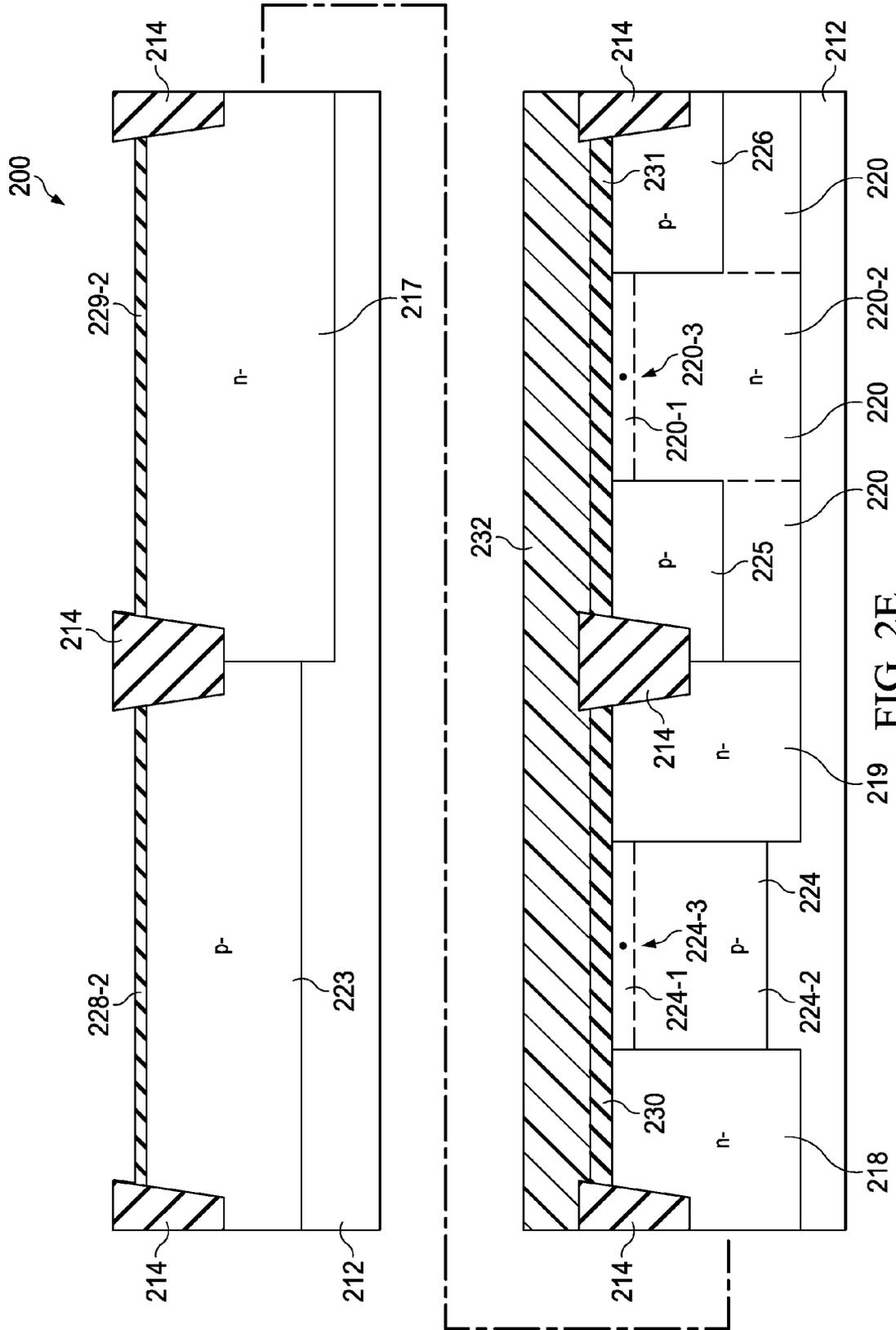


FIG. 2E

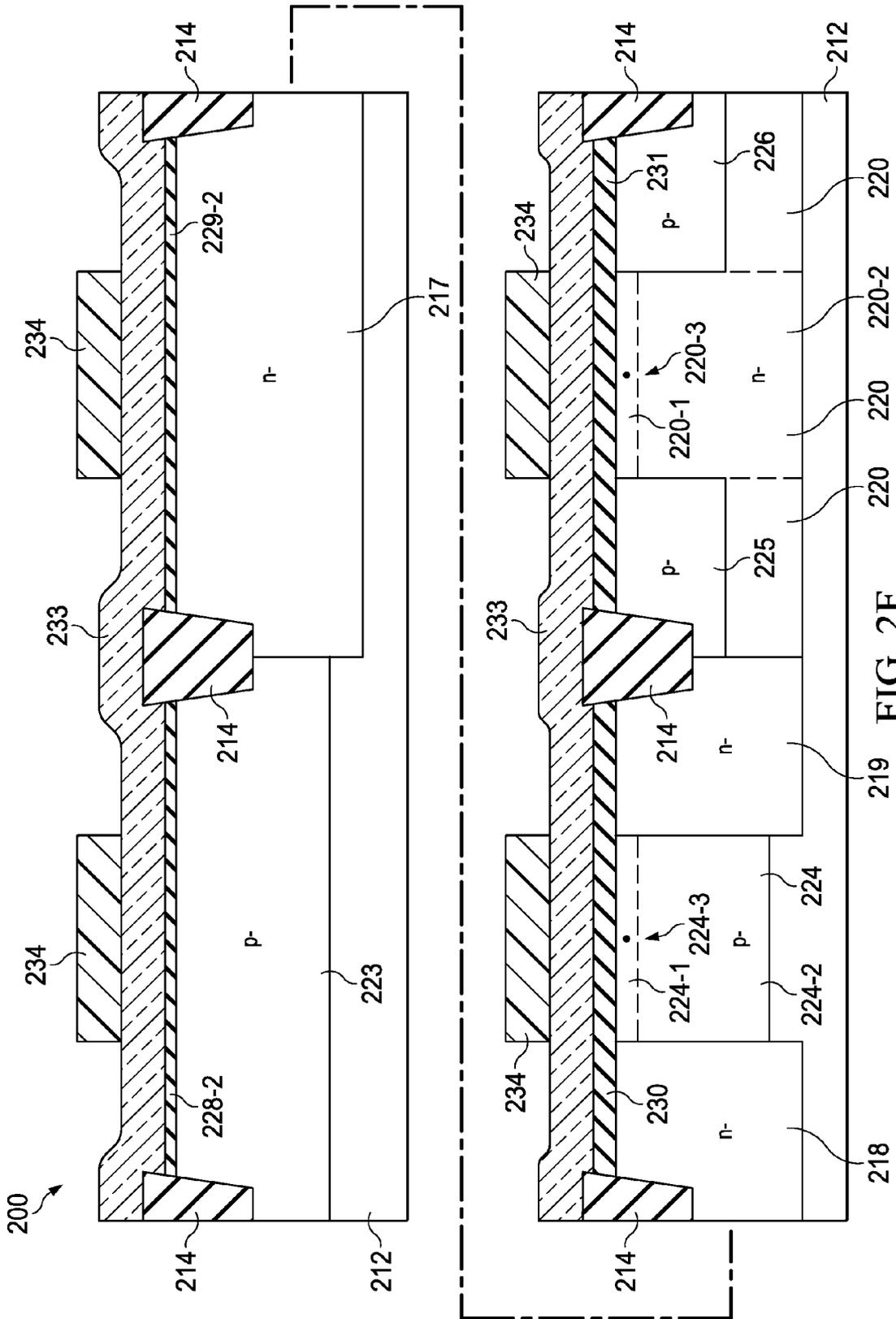


FIG. 2F

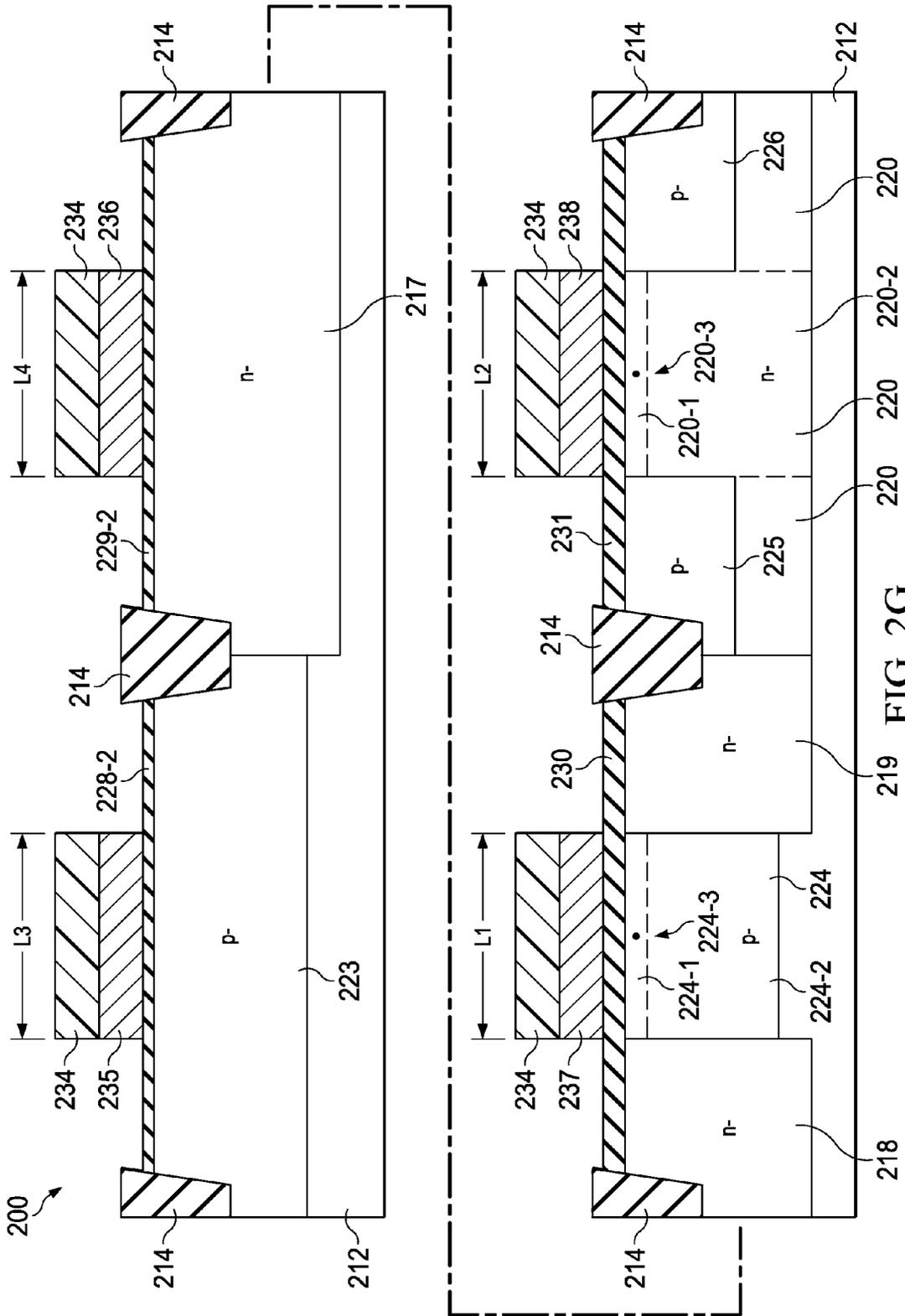


FIG. 2G

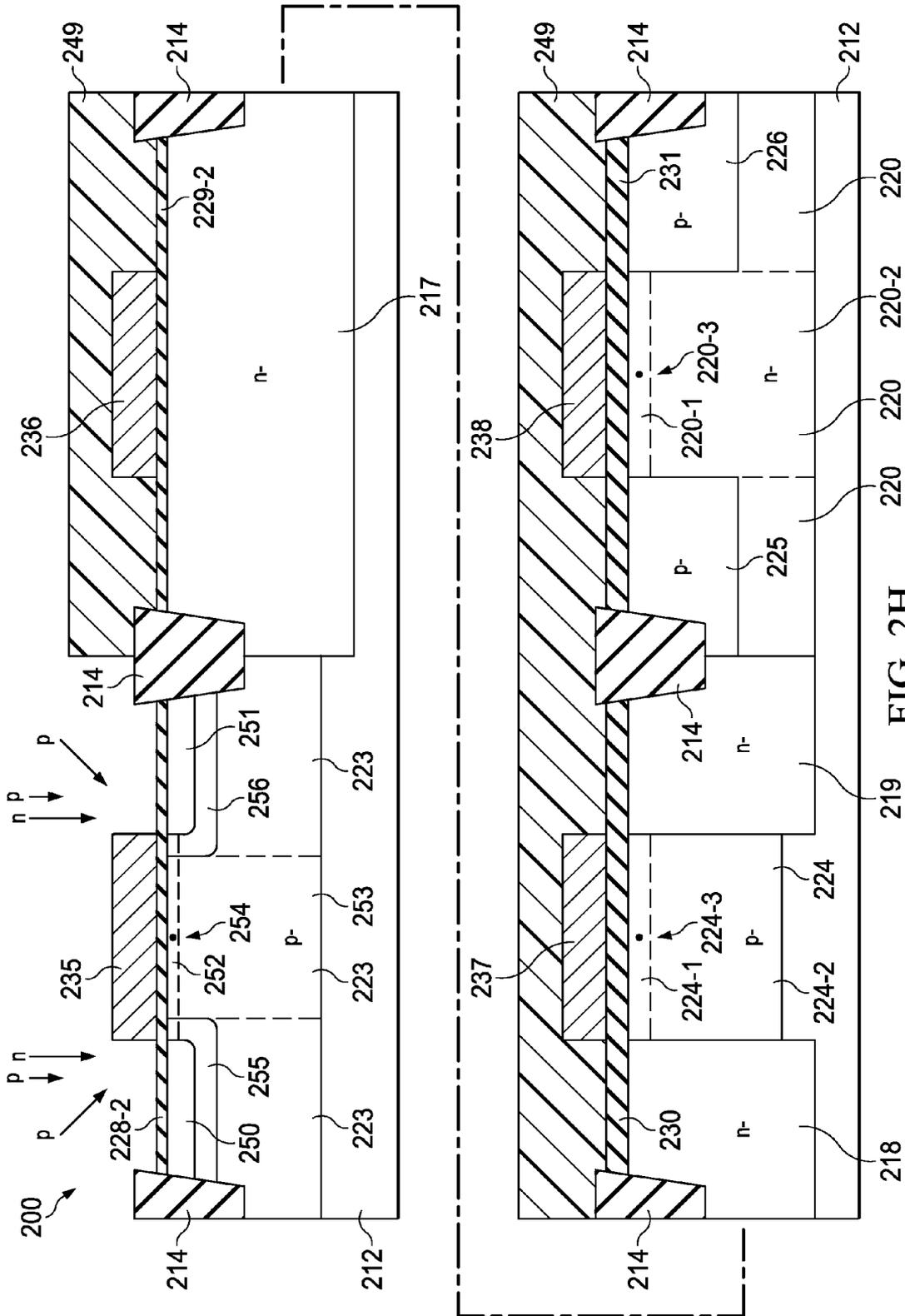


FIG. 2H

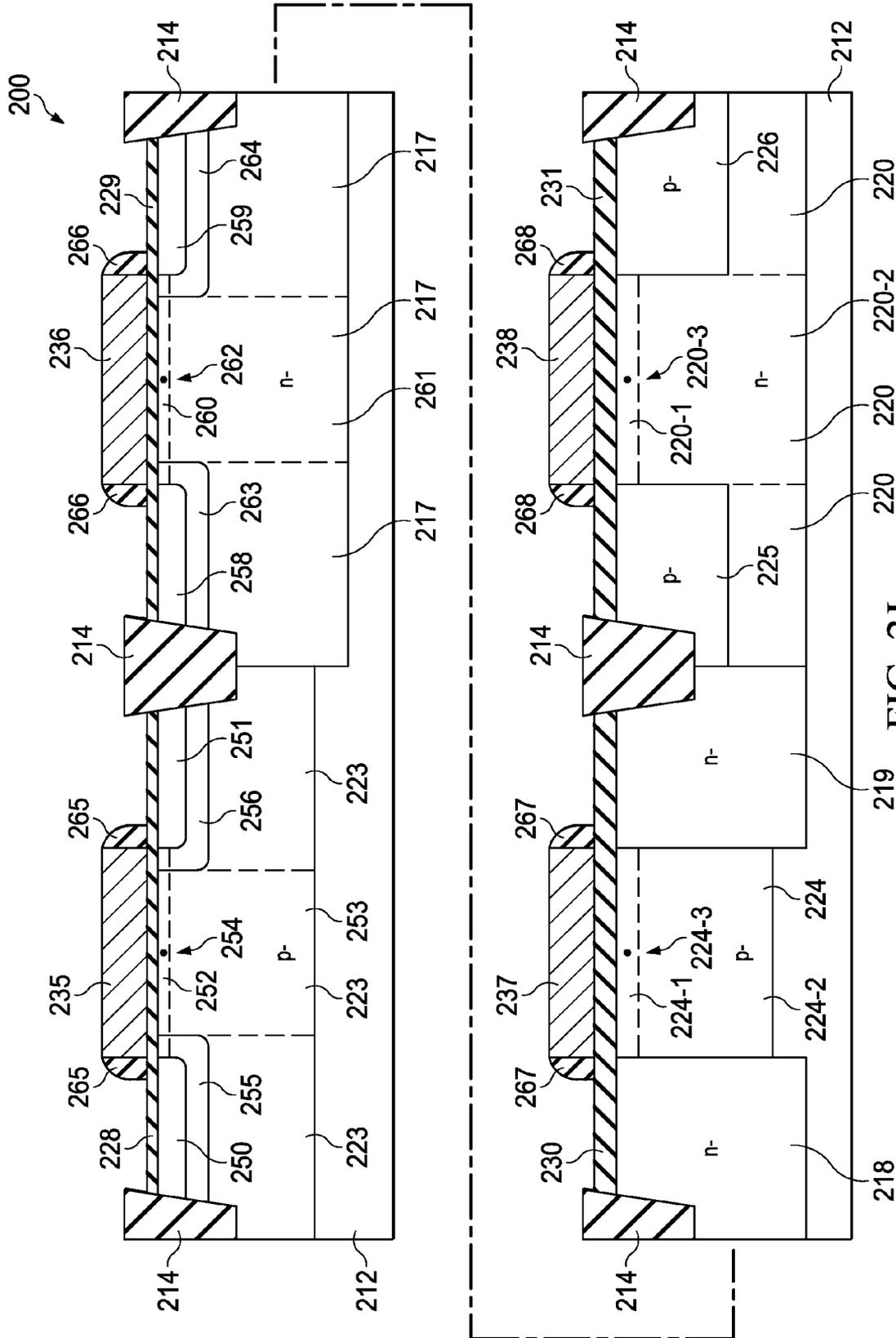


FIG. 2J

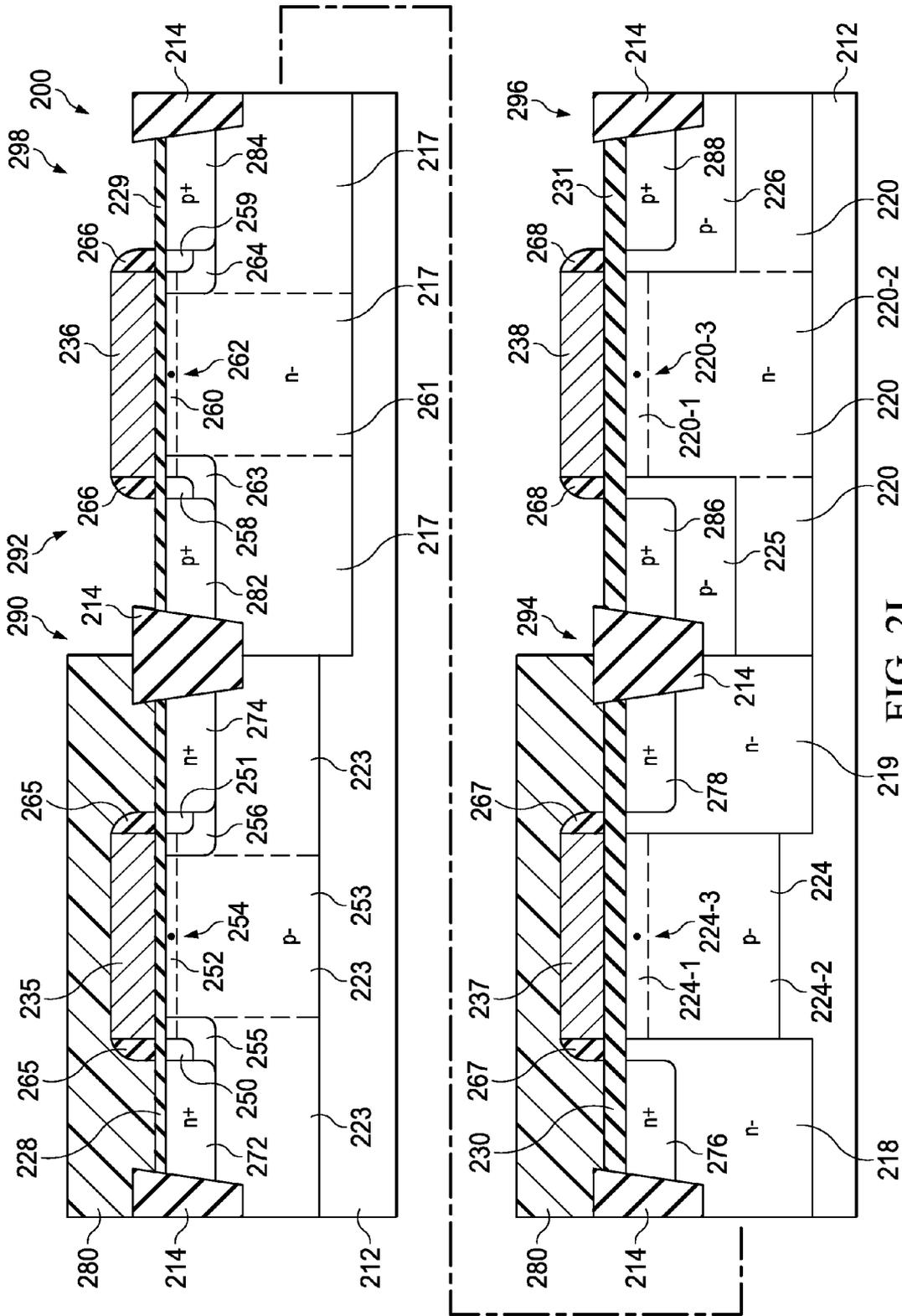
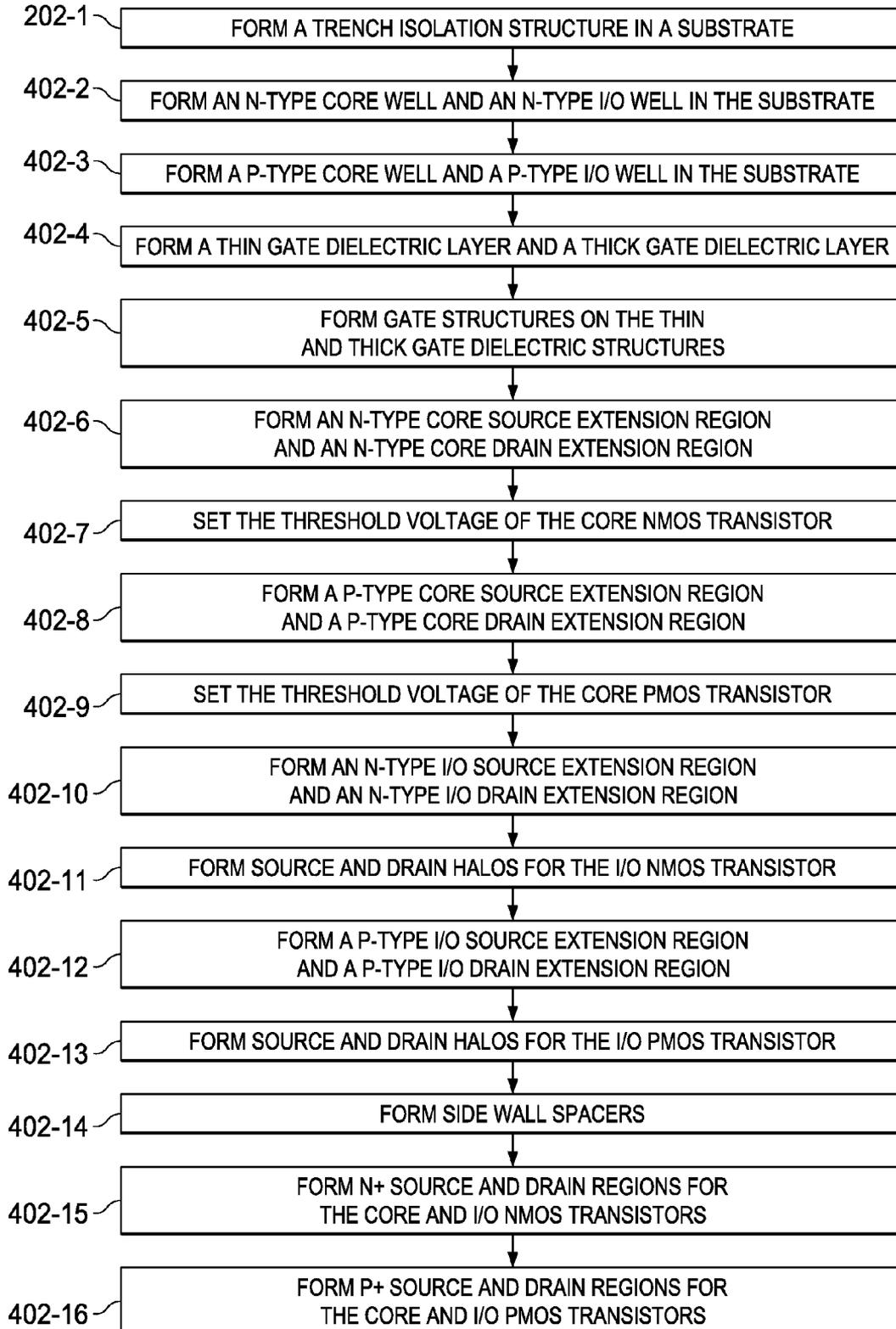


FIG. 2L

FIG. 4A

400



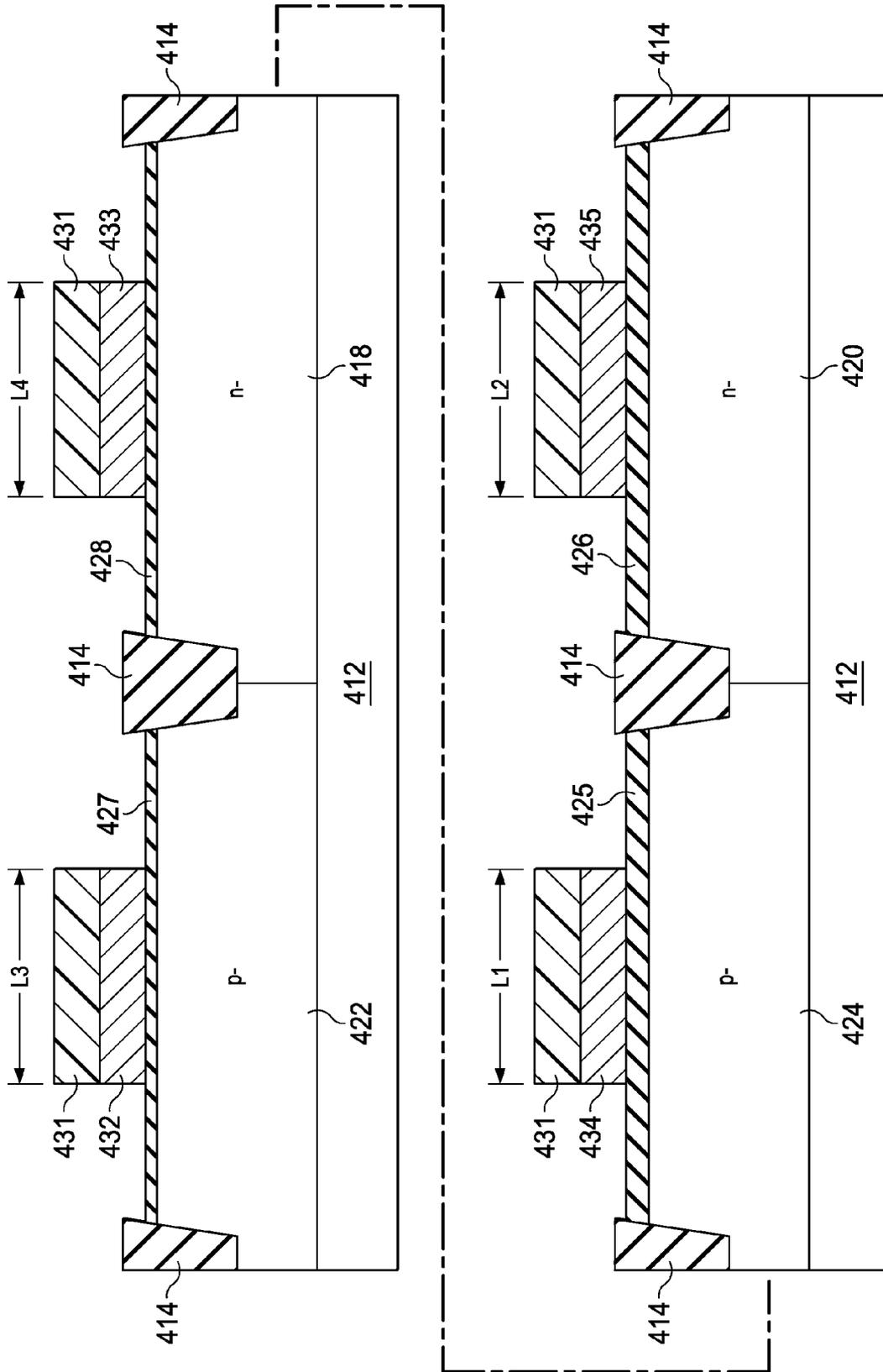


FIG. 4B

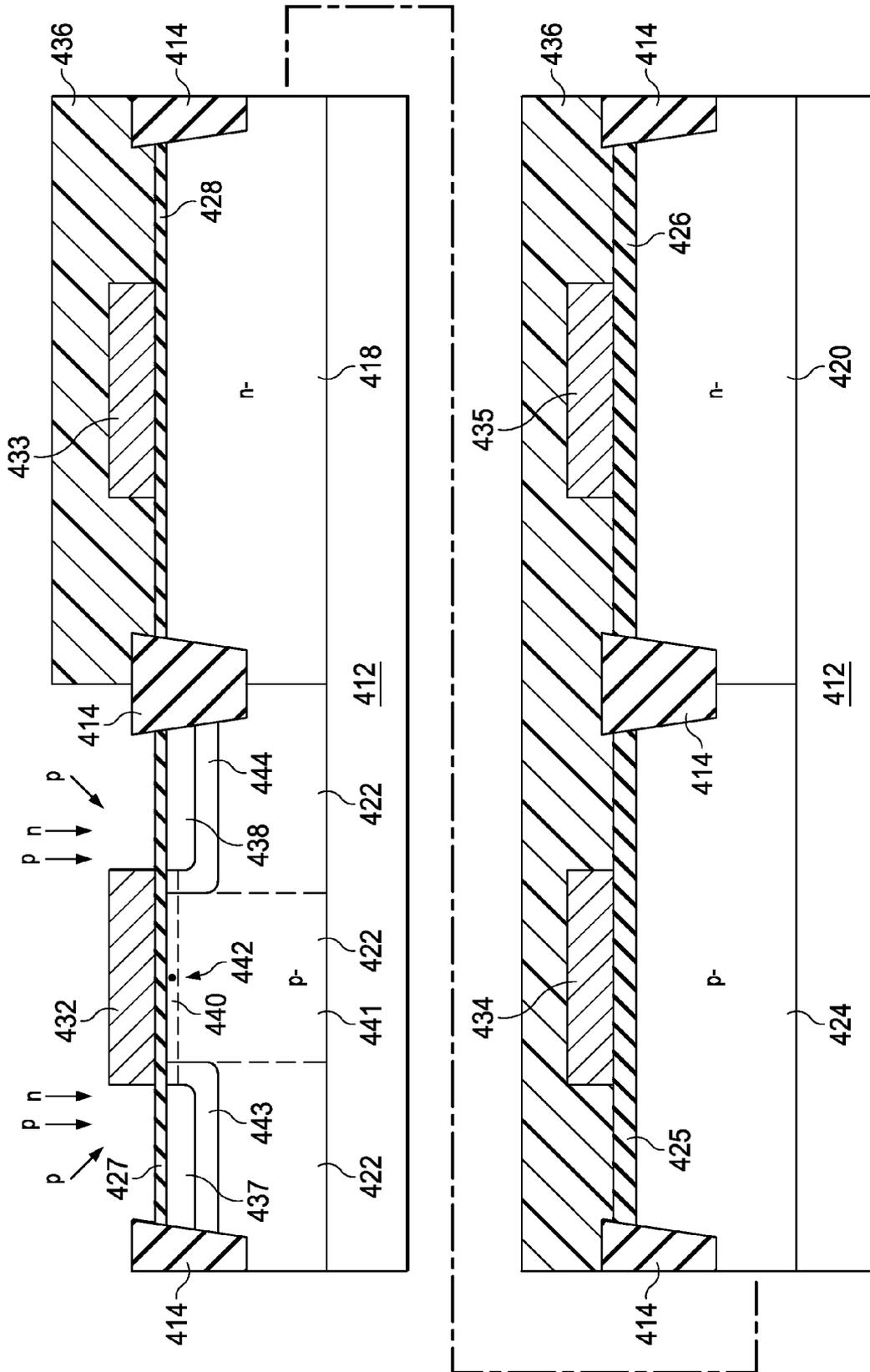


FIG. 4C

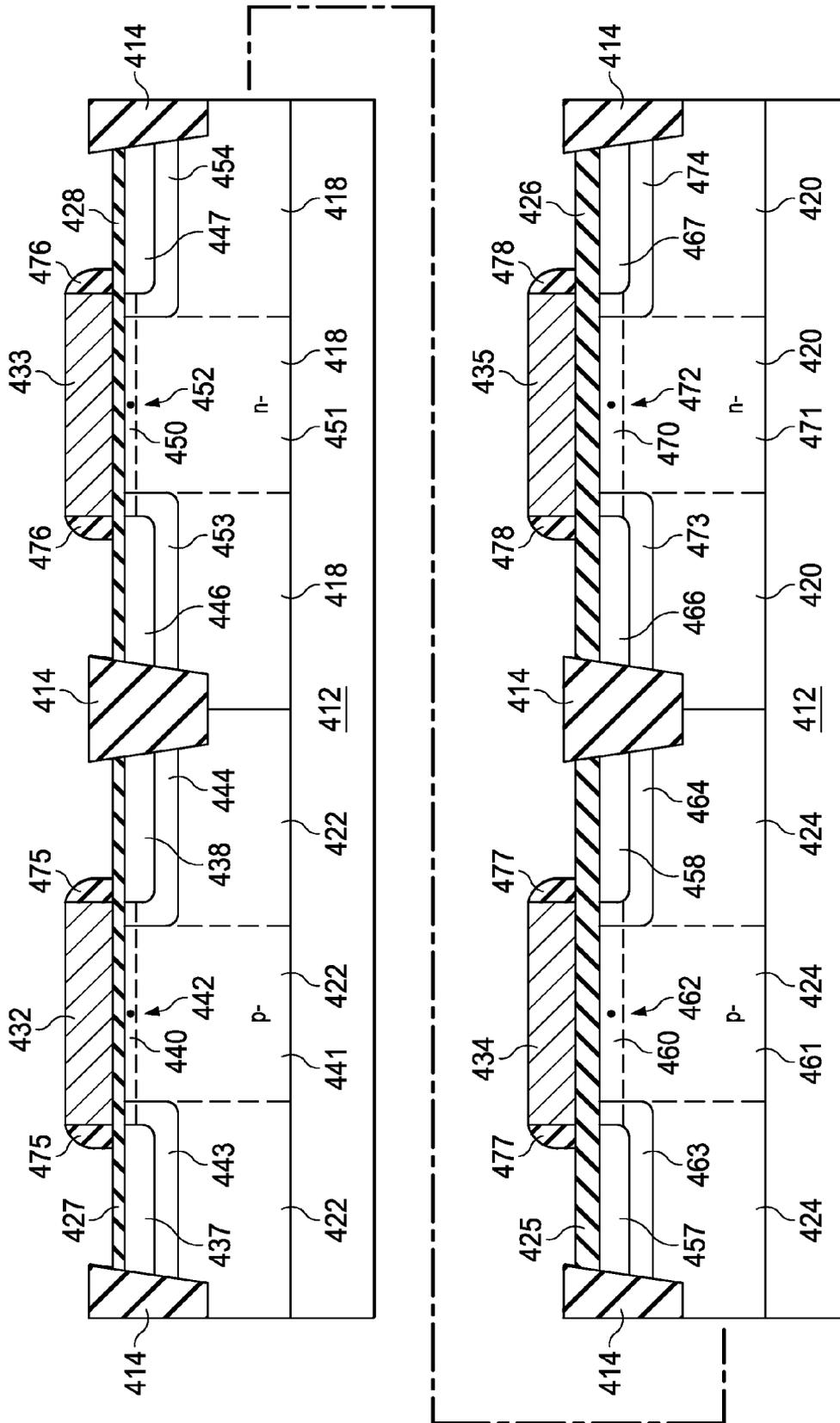


FIG. 4G

FIG. 5

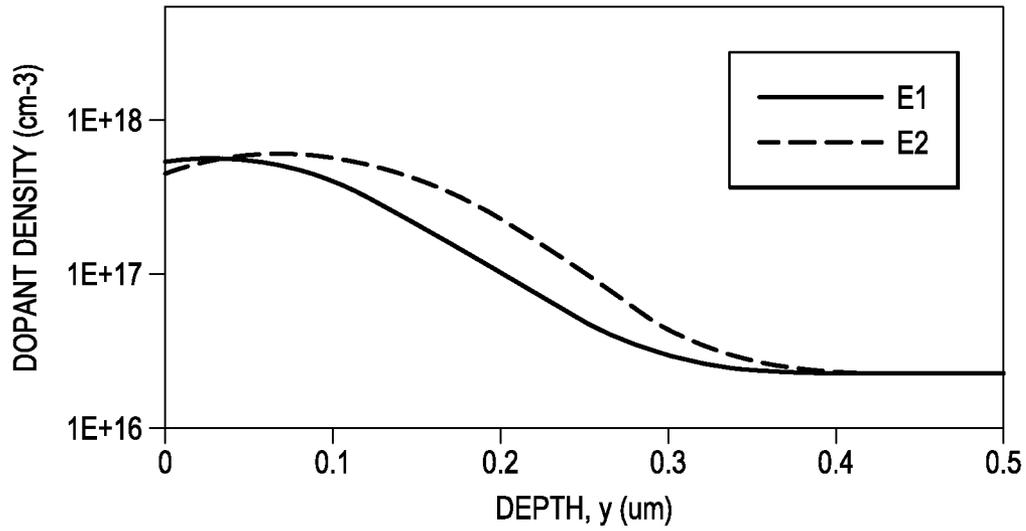
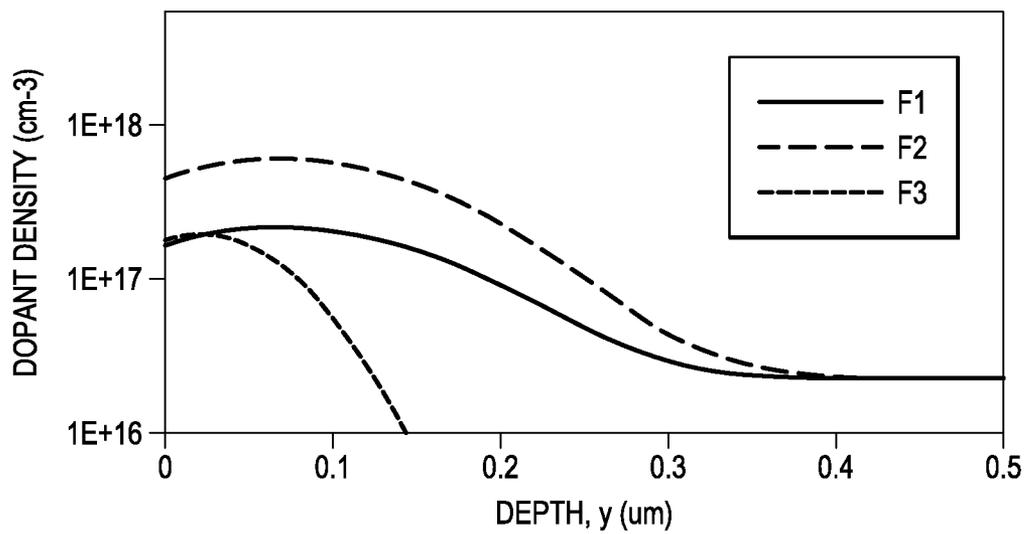


FIG. 6



**LOW-COST CMOS STRUCTURE WITH
DUAL GATE DIELECTRICS AND METHOD
OF FORMING THE CMOS STRUCTURE**

CROSS REFERENCE TO RELATED
APPLICATIONS

This application is a divisional of U.S. Nonprovisional patent application Ser. No. 13/789,477, filed Mar. 7, 2013, the contents of which are herein incorporated by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to a CMOS structure and, more particularly, to a low-cost CMOS structure with dual gate dielectrics and a method of forming the CMOS structure.

DESCRIPTION OF THE RELATED ART

A complimentary metal oxide semiconductor (CMOS) circuit is a circuit that includes one or more n-channel (NMOS) transistors as well as one or more p-channel (PMOS) transistors. Physically, the NMOS and PMOS transistors each have spaced-apart source and drain regions, which are separated by a channel region, and a gate that lies over and is insulated from the channel region by a gate dielectric.

The source and drain regions, which are formed in a well of the opposite conductivity type, each includes an extension region and a main region that touches the extension region. The main region has a heavier dopant concentration than the extension region. The well, in turn, includes the channel region, which is a surface region of the well that touches the gate dielectric, and a below-the-channel region that touches and lies below the channel region.

Semiconductor chips commonly include two types of CMOS circuits: core CMOS circuits which perform the functionality of the chip, and input/output (I/O) CMOS circuits which connect the core CMOS circuits to the outside world. The core CMOS circuits typically operate with supply voltages that are lower than the supply voltages that are used by the I/O circuits.

When the core CMOS circuits utilize supply voltages that are lower than the supply voltages utilized by the I/O CMOS circuits, the NMOS and PMOS transistors in the core CMOS circuits are physically formed to have gate dielectrics that are thinner than the gate dielectrics of the NMOS and PMOS transistors in the I/O CMOS circuits. As a result, a CMOS structure with dual gate dielectrics is a type of CMOS structure that includes NMOS and PMOS transistors with thin gate dielectrics, and NMOS and PMOS transistors with thick gate dielectrics.

There are three common approaches to forming a CMOS structure with dual gate dielectrics. In a first approach, which is the most economical, the NMOS transistors in the core CMOS circuits and the NMOS transistors in the I/O CMOS circuits are formed as identical structures, except for the gate dielectrics, where the NMOS transistors in the core CMOS circuits have thinner gate dielectrics than the NMOS transistors in the I/O CMOS circuits. Similarly, the PMOS transistors in the core CMOS circuits and the PMOS transistors in the I/O CMOS circuits are formed as identical structures, except for the gate dielectrics, where the PMOS

transistors in the core CMOS circuits have thinner gate dielectrics than the PMOS transistors in the I/O CMOS circuits.

In the first approach, a mask is used to form the gate dielectrics with two different thicknesses. For example, gate dielectric layers can be grown on each well. The growth then continues until the gate dielectric layers have reached the thickness required by the NMOS and PMOS transistors in the core CMOS circuits.

Following this, a mask is formed on the top surfaces of the gate dielectric layers to cover and protect the gate dielectric layers that lie over the wells of the NMOS and PMOS transistors of the core CMOS circuits. The mask also exposes the gate dielectric layers that lie over the wells of the NMOS and PMOS transistors of the I/O CMOS circuits. After the mask has been formed, the exposed gate dielectric layers are further grown until the gate dielectric layers over the wells of the NMOS and PMOS transistors of the I/O CMOS circuits have reached the thickness required by the NMOS and PMOS transistors in the I/O CMOS circuits.

In a second approach to forming a dual gate structure, in addition to using a mask to form the gate dielectrics with two different thicknesses as in the first approach, a pair of p-well masks is also used to form the p-type wells of the NMOS transistors. The first p-well mask of the pair exposes a substrate region where the p-type wells of the NMOS transistors in the core CMOS circuits are to be formed. The second p-well mask of the pair, which is formed after the first p-well mask has been removed, exposes a substrate region where the p-type wells of the NMOS transistors in the I/O CMOS circuits are to be formed.

As a result, when acceptor-type impurity atoms are implanted through the first and second p-well masks to form the p-type wells, the atoms are implanted so that the average dopant concentration of the channel region of each of the NMOS transistors in the core CMOS circuits is greater than the average dopant concentration of the channel region of each of the NMOS transistors in the I/O CMOS circuits.

In addition, the acceptor-type impurity atoms are also implanted through the first and second p-well masks so that the dopant profile of the below-the-channel region of each of the NMOS transistors in the core CMOS circuits is substantially different than the dopant profile of the below-the-channel region of each of the NMOS transistors in the I/O CMOS circuits.

Further, a pair of n-well masks is also used to form the n-type wells of the PMOS transistors. The first n-well mask of the pair exposes a substrate region where the n-type wells of the PMOS transistors in the core CMOS circuits are to be formed. The second n-well mask, which is formed after the first n-well mask has been removed, exposes a substrate region where the n-type wells of the PMOS transistors in the I/O CMOS circuits are to be formed.

As a result, when donor-type impurity atoms are implanted through the first and second n-well masks to form the n-type wells, the atoms are implanted so that the average dopant concentration of the channel region of each of the PMOS transistors in the core CMOS circuits is greater than the average dopant concentration of the channel region of each of the PMOS transistors in the I/O CMOS circuits.

In addition, the donor-type impurity atoms are also implanted through the first and second n-well masks so that the dopant profile of the below-the-channel region of each of the PMOS transistors in the core CMOS circuits is substantially different than the dopant profile of the below-the-channel region of each of the PMOS transistors in the I/O CMOS circuits. Otherwise, in the second approach, the

NMOS transistors in the core and the I/O CMOS circuits are formed at the same time, while the PMOS transistors in the core and the I/O CMOS circuits are also formed at the same time.

In a third approach to forming a dual gate structure, in addition to using a mask to form the gate dielectrics with two different thicknesses as in the first approach, a pair of n-extension masks is used to form the n-type source and drain extension regions of the NMOS transistors, counter dope the channel regions of the NMOS transistors in the I/O CMOS circuits, and optionally form any p-type halo or pocket regions.

The first n-extension mask of the pair exposes the gates and the p-type wells of the NMOS transistors in the core CMOS circuit, while the second n-extension mask of the pair exposes the gates and the p-type wells of the NMOS transistors in the I/O CMOS circuits. When the first n-extension mask is in place, donor-type impurity atoms are implanted into the p-type wells of the NMOS transistors in the core CMOS circuits. The implant forms spaced-apart n-type source and drain extension regions in each p-type well of the NMOS transistors of the core CMOS circuits. The donor-type impurity atoms are blocked from the p-type channel regions by the gates.

While the first n-extension mask remains in place, acceptor-type impurity atoms can be optionally implanted into the p-type wells of the NMOS transistors in the core CMOS circuits at a number of angles. The implant forms spaced-apart p-type halo or pocket regions in each p-type well of the NMOS transistors in the core CMOS circuits. The p-type halo or pocket regions in a p-type well touch the n-type source and drain extension regions and the p-type channel region that are in the p-type well. The implant energy is insufficient to penetrate through the gates into the channel regions.

After the first n-extension mask has been removed and the second n-extension mask has been put in place, donor-type impurity atoms are implanted into the p-type wells of the NMOS transistors in the I/O CMOS circuits. The implant forms spaced-apart n-type source and drain extension regions in each p-type well of the NMOS transistors in the I/O CMOS circuits. The donor-type impurity atoms are blocked from the p-type channel region by the gate.

While the second n-extension mask is still in place, donor-type impurity atoms are again implanted into the p-type wells of the NMOS transistors in the I/O CMOS circuits. This time, however, the donor-type impurity atoms are implanted with an implant energy that is sufficient to penetrate through the gates into the channel regions and counter dope the channel regions.

The introduction of donor-type impurity atoms into a channel region having only acceptor-type impurity atoms has the net effect of reducing the average dopant concentration of the acceptor-type impurity atoms in the channel region. In a counter doped channel region, the channel region has both acceptor-type and donor-type impurity atoms.

While the second n-extension mask of the pair remains in place, acceptor-type impurity atoms can be optionally implanted into the p-type wells of the NMOS transistors in the I/O CMOS circuits at a number of angles. The implant forms spaced-apart p-type halo or pocket regions in each p-type well of the NMOS transistors in the I/O CMOS circuits. The implant energy is insufficient to penetrate through the gates into the channel regions.

Further, a pair of p-extension masks is used to form the p-type source and drain extension regions of the PMOS

transistors, counter dope the channel regions of the PMOS transistors in the I/O CMOS circuits, and optionally form any n-type halo or pocket regions. The first p-extension mask of the pair exposes the gates and the n-type wells of the PMOS transistors in the core CMOS circuit, while the second p-extension mask of the pair exposes the gates and the n-type wells of the PMOS transistors in the I/O CMOS circuits.

When the first p-extension mask is in place, acceptor-type impurity atoms are implanted into the n-type wells of the PMOS transistors of the core CMOS circuits. The implant forms spaced-apart p-type source and drain extension regions in each n-type well of the PMOS transistors in the core CMOS circuits. The acceptor-type impurity atoms are blocked from the n-type channel regions by the gates.

While the first p-extension mask remains in place, donor-type impurity atoms can be optionally implanted into the n-type wells of the PMOS transistors of the core CMOS circuits at a number of angles. The implant forms spaced-apart n-type halo or pocket regions in each n-type well of the PMOS transistors in the core CMOS circuits. The n-type halo or pocket regions in an n-type well touch the p-type source and drain extension regions and the n-type channel region that are in the n-type well. The implant energy is insufficient to penetrate through the gates into the channel regions.

After the first p-extension mask has been removed and the second p-extension mask has been put in place, acceptor-type impurity atoms are implanted into the n-type wells of the PMOS transistors of the I/O CMOS circuits. The implant forms spaced-apart p-type source and drain extension regions in each n-type well of the PMOS transistors in the I/O CMOS circuits. The acceptor-type impurity atoms are blocked from the n-type channel region by the gate.

While the second p-extension mask is still in place, acceptor-type impurity atoms are again implanted into the n-type wells of the PMOS transistors of the I/O CMOS circuits. This time, however, the acceptor-type impurity atoms are implanted with an implant energy that is sufficient to penetrate through the gates into the channel regions and counter dope the channel regions. The introduction of acceptor-type impurity atoms into a channel region having substantially only donor-type impurity atoms has the net effect of reducing the average dopant concentration of the donor-type impurity atoms in the channel region.

While the second p-extension mask of the pair remains in place, donor-type impurity atoms can be optionally implanted into the n-type wells of the PMOS transistors of the I/O CMOS circuits at a number of angles. The implant forms spaced-apart n-type halo or pocket regions in each n-type well of the PMOS transistors of the I/O CMOS circuits. The implant energy is insufficient to penetrate through the gates into the channel regions.

Otherwise, in the third approach, the NMOS transistors in the core and I/O CMOS circuits are formed at the same time, while the PMOS transistors in the core and I/O CMOS circuits are also formed at the same time. Although there are three common methods of forming a CMOS structure with dual gate dielectrics, there is a need for other low-cost methods of forming a CMOS structure with dual gate dielectrics.

SUMMARY OF THE INVENTION

The present invention provides a dual gate dielectric semiconductor structure. The semiconductor structure of the present invention includes a semiconductor region and a first

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body region that touches the semiconductor region. The first body region has a first channel region and a below-the-first channel region that touches and lies below the first channel region. The first channel region has a first middle point. The first channel region at the first middle point includes a first type of impurity atoms, is substantially free of a second type of impurity atoms, and has an average dopant concentration. The below-the-first channel region has a dopant profile. The semiconductor structure also includes a first source region and a first drain region. The first source region touches the first body region, and includes substantially more of the second type of impurity atoms than the first type of impurity atoms. The first drain region touches the first body region, is spaced apart from the first source region, and includes substantially more of the second type of impurity atoms than the first type of impurity atoms. The first middle point lies mid-way between the first source and drain regions. The semiconductor structure additionally includes a second body region that touches the semiconductor region and lies spaced apart from the first body region. The second body region has a second channel region and a below-the-second channel region that touches and lies below the second channel region. The second channel region has a second middle point. The second channel region at the second middle point includes the first type of impurity atoms, is substantially free of the second type of impurity atoms, and has an average dopant concentration that is less than the average dopant concentration of the first channel region at the first middle point. The below-the-second channel region has a dopant profile that is substantially identical to the dopant profile of the below-the-first channel region. The semiconductor structure further includes a second source region and a second drain region. The second source region touches the second body region, and includes substantially more of the second type of impurity atoms than the first type of impurity atoms. The second drain region touches the second body region. The second drain region is spaced apart from the second source region and includes substantially more of the second type of impurity atoms than the first type of impurity atoms. The second middle point lies mid-way between the second source and second regions.

The present invention also includes a method of forming a dual gate semiconductor structure. The method includes forming a first mask that exposes a first well and a first gate to a first implant, and protects a second well and a second gate from the first implant. The first well and the second well are formed in a semiconductor substrate. A thin gate dielectric touches and lies between the first well and the first gate. A thick gate dielectric touches and lies between the second well and the second gate. The first and second wells include a first type of impurity atoms, are substantially free of a second type of impurity atoms, and have substantially identical dopant profiles when the first mask is formed. The method also includes implanting the second type of impurity atoms through the first mask into the first well to form a first source extension region and a first drain extension region that lies spaced apart from the first source extension region. The first well includes a first channel region that lies between the first source extension region and the first drain extension region. The first channel region has a first middle point that lies mid-way between the first source extension region and the first drain extension region. The first channel region at the first middle point includes the first type of impurity atoms, is substantially free of the second type of impurity atoms, and has an average dopant concentration. The method additionally includes implanting the first type of impurity atoms through the first mask, the first gate, and the

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thin gate dielectric into the first channel region to raise the average dopant concentration of the first channel region.

The present invention also includes a method of forming a dual gate semiconductor structure that reduces the fabrication costs. The method includes implanting a first type of impurity atoms into a substrate to simultaneously form a first core well, a first I/O source extension region, a first I/O drain extension region, and a first I/O well. The method also includes implanting a second type of impurity atoms into the substrate to simultaneously form a second core well, a second I/O well, a second I/O source extension region, and a second I/O drain extension region. The second I/O well touches the first I/O source extension region and the first I/O drain extension region. The second I/O source extension region and the second I/O drain extension region touch the first I/O well. The method additionally includes implanting the first type of impurity atoms into the second core well to simultaneously form a first core source extension region and a first core drain extension region, and implanting the second type of impurity atoms into the first core well to simultaneously form a second core source extension region and a second core drain extension region. Further, the method includes simultaneously implanting the first type of impurity atoms into the first core source extension region to form a first core main source region that touches the first core source extension region, the first core drain extension region to form a first core main drain region that touches the first core drain extension region, the first I/O source extension region to form a first I/O main source region that touches the first I/O source extension region, and the first I/O drain extension region to form a first I/O main drain region that touches the first I/O drain extension region.

A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description and accompanying drawings which set forth an illustrative embodiment in which the principals of the invention are utilized.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view illustrating an example of a dual gate dielectric CMOS structure **100** in accordance with the present invention.

FIGS. 2A-2L illustrate an example of a method **200** of forming a dual gate dielectric CMOS structure in accordance with the present invention. FIG. 2A is a flow chart of method **200**. FIGS. 2B-2L are cross-sectional views of method **200**.

FIG. 3 is a cross-sectional view illustrating an example of a dual gate dielectric CMOS structure **300** in accordance with an alternate embodiment of the present invention.

FIGS. 4A-4I illustrate an example of a method **400** of forming a dual gate dielectric CMOS structure in accordance with an alternate embodiment of the present invention. FIG. 4A is a flow chart of method **400**. FIGS. 4B-4I are cross-sectional views of method **400**.

FIG. 5 is a graph illustrating the boron dopant profile of an NMOS core well below an overlying gate in accordance with the present invention.

FIG. 6 is a graph illustrating the dopant profile of an NMOS I/O well below an overlying gate structure in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows a cross-sectional view that illustrates an example of a dual gate dielectric CMOS structure **100** in

accordance with the present invention. As described in greater detail below, impurity atoms of a single type are implanted through a gate and a thin gate dielectric into a channel region that has substantially only the same type of impurity atoms at a middle point of the channel region. The implant increases the average dopant concentration of the single type of impurity atoms in the channel region to adjust the threshold voltage of a thin gate dielectric transistor.

As shown in FIG. 1, CMOS structure 100 includes a base structure 110. Base structure 110, in turn, includes a p-type single-crystal-silicon substrate 112 and a trench isolation structure 114. Base structure 110 also includes a p-type body region 116 that touches substrate 112 and trench isolation structure 114. Body region 116 has a higher average dopant concentration than substrate 112.

P-type body region 116, in turn, includes a p-type channel region 117, a middle point 118 of channel region 117, and a p-type below-the-channel region 119 that touches and lies directly below p-type channel region 117. P-type channel region 117 at the middle point 118 is substantially free of donor-type impurity atoms. In addition, p-type channel region 117 has a channel length L1 and an average dopant concentration, while p-type below-the-channel region 119 has a dopant profile directly below middle point 118. A channel region is the surface portion of the body region that influences the threshold voltage of the transistor. A dopant profile can be graphically represented with a dopant concentration axis and a depth down from the top surface of the region axis.

Base structure 110 further includes an n-type source 120 and an n-type drain 121 that each touch p-type body region 116. The n-type source 120 and drain 121 are spaced apart. In addition, n-type source 120 includes an n-type source extension region 122 and an n-type main source region 123 that touches region 122.

Further, n-type drain 121 includes an n-type drain extension region 124 and an n-type main drain region 125 that touches region 124. Main source region 123 has a greater dopant concentration than extension region 122, while main drain region 125 has a greater dopant concentration than extension region 124. In addition, middle point 118 lies mid-way between source 120 and drain 121.

Base structure 110 also includes a p-type halo 126 that touches p-type body region 116 and n-type source 120, and a p-type halo 127 that touches p-type body region 116 and n-type drain 121. The p-type halos 126 and 127, which are spaced apart, have higher average dopant concentrations than the adjoining portions of below-the-channel region 119. (The halos 126 and 127 can optionally be omitted.)

In addition to base structure 110, CMOS structure 100 also includes a thin gate dielectric structure 130 that touches and lies above p-type channel region 117, and a conductive gate 131 that touches thin gate dielectric structure 130 and lies above p-type channel region 117 and thin gate dielectric structure 130. CMOS structure 100 further includes a sidewall spacer 132 that touches and laterally surrounds gate 131.

The combination of p-type body region 116, p-type channel region 117, p-type below-the-channel region 119, n-type source 120, n-type drain 121, p-type halo 126, p-type halo 127, thin gate dielectric structure 130, conductive gate 131, and sidewall spacer 132 define a thin gate dielectric (core) NMOS transistor 133.

As further shown in FIG. 1, base structure 110 also includes a p-type body region 135 that touches substrate 112. Body region 135 has a higher average dopant concentration than substrate 112. In addition, p-type body region 135, in

turn, includes a p-type channel region 136, a middle point 137 of channel region 136, and a p-type below-the-channel region 138 that touches and lies directly below p-type channel region 136.

P-type channel region 136 at the middle point 137 is substantially free of donor-type impurity atoms. In addition, p-type channel region 136 has a channel length L2 that is substantially greater (e.g., 10×) than the channel length L1 of p-type channel region 117, and an average dopant concentration that is substantially less than the average dopant concentration of p-type channel region 117. In addition, p-type below-the-channel region 138 has a dopant profile directly below middle point 137 that is substantially identical to the dopant profile of p-type below-the-channel region 119 directly below middle point 118.

Base structure 110 further includes an n-type source 140 and an n-type drain 141 that each touch p-type body region 135. The n-type source 140 and drain 141 are spaced apart. In addition, n-type source 140 includes an n-type source extension region 142 and an n-type main source region 143 that touches region 142, while n-type drain 141 includes an n-type drain extension region 144 and an n-type main drain region 145 that touches region 144.

N-type main source region 143 touches n-type source extension region 142 so that only n-type source extension region 142 lies horizontally between p-type body region 135 and n-type main source region 143. N-type main drain region 145 touches n-type drain extension region 144 so that only n-type drain extension region 144 lies horizontally between p-type body region 135 and n-type main drain region 145. Main source region 143 has a greater dopant concentration than extension region 142, while main drain region 145 has a greater dopant concentration than extension region 144. Further, middle point 137 lies mid-way between source 140 and drain 141.

In addition, CMOS structure 100 includes a thick gate dielectric structure 146 that touches and lies above p-type channel region 136, and a conductive gate 147 that touches thick gate dielectric structure 146 and lies above p-type channel region 136 and thick gate dielectric structure 146. (Thick gate dielectric structure 146 is thicker than thin gate dielectric structure 130.) CMOS structure 100 also includes a sidewall spacer 148 that touches and laterally surrounds gate 147.

The combination of p-type body region 135, p-type channel region 136, p-type below-the-channel region 138, n-type source 140, n-type drain 141, thick gate dielectric structure 146, conductive gate 147, and sidewall spacer 148 define a thick gate dielectric (I/O) NMOS transistor 150.

As additionally shown in FIG. 1, base structure 110 includes an n-type body region 155 that touches substrate 112 and trench isolation structure 114. N-type body region 155, in turn, includes an n-type channel region 156, a middle point 157 of channel region 156, and an n-type below-the-channel region 158 that touches and lies directly below n-type channel region 156.

N-type channel region 156 at the middle point 157 is substantially free of acceptor-type impurity atoms. In addition, n-type channel region 156 has a channel length L3, and an average dopant concentration, while n-type below-the-channel region 158 has a dopant profile directly below middle point 157.

Base structure 110 further includes a p-type source 160 and a p-type drain 161 that each touch n-type body region 155. The p-type source 160 and drain 161 are spaced apart.

In addition, p-type source **160** includes a p-type source extension region **162** and a p-type main source region **163** that touches region **162**.

Further, p-type drain **161** includes a p-type drain extension region **164** and a p-type main drain region **165** that touches region **164**. Main source region **163** has a greater dopant concentration than extension region **162**, while main drain region **165** has a greater dopant concentration than extension region **164**. In addition, middle point **157** lies mid-way between source **160** and drain **161**.

Base structure **110** additionally includes an n-type halo **166** that touches n-type body region **155** and p-type source **160**, and an n-type halo **167** that touches n-type body region **155** and p-type drain **161**. The n-type halos **166** and **167**, which are spaced apart, have higher average dopant concentrations than the adjoining portions of below-the-channel region **158**. (The halos **166** and **167** can optionally be omitted.)

In addition, CMOS structure **100** includes a thin gate dielectric structure **168** that touches and lies above n-type channel region **156**, and a conductive gate **169** that touches thin gate dielectric structure **168** and lies above n-type channel region **156** and thin gate dielectric structure **168**. CMOS structure **100** also includes a sidewall spacer **170** that touches and laterally surrounds gate **169**.

The combination of n-type body region **155**, n-type channel region **156**, n-type below-the-channel region **158**, p-type source **160**, p-type drain **161**, n-type halo **166**, n-type halo **167**, thin gate dielectric structure **168**, conductive gate **169**, and sidewall spacer **170** define a thick gate dielectric (core) PMOS transistor **172**.

As further shown in FIG. 1, base structure **110** also includes an n-type body region **175** that touches substrate **112**. N-type body region **175**, in turn, includes an n-type channel region **176**, a middle point **177** of channel region **176**, and an n-type below-the-channel region **178** that touches and lies directly below n-type channel region **176**.

N-type channel region **176** at the middle point **177** is substantially free of acceptor-type of impurity atoms. In addition, n-type channel region **176** has a channel length **L4** that is substantially greater (e.g., **10X**) than the channel length **L3** of n-type channel region **156**, and an average dopant concentration that is substantially less than the average dopant concentration of n-type channel region **156**. Further, n-type below-the-channel region **178** has a dopant profile directly below middle point **177** that is substantially identical to the dopant profile of n-type below-the-channel region **158** directly below middle point **157**.

Base structure **110** also includes a p-type source **180** and a p-type drain **181** that each touch n-type body region **175**. The p-type source **180** and drain **181** are spaced apart. In addition, p-type source **180** includes a p-type source extension region **182** and a p-type main source region **183** that touches region **182**. Further, p-type drain **181** includes a p-type drain extension region **184** and a p-type main drain region **185** that touches region **184**.

P-type main source region **183** touches p-type source extension region **182** so that only p-type source extension region **182** lies horizontally between n-type body region **175** and p-type main source region **183**. P-type main drain region **185** touches p-type drain extension region **184** so that only p-type drain extension region **184** lies horizontally between n-type body region **175** and p-type main drain region **185**.

The p-type source extension region **182** and the p-type drain extension region **184** are spaced apart from substrate **112**. In addition, main source region **183** has a greater dopant concentration than extension region **182**, while main drain

region **185** has a greater dopant concentration than extension region **184**. Further, middle point **177** lies mid-way between source **180** and drain **181**.

In addition, CMOS structure **100** includes a thick gate dielectric structure **186** that touches and lies above n-type channel region **176**, and a conductive gate **187** that touches thick gate dielectric structure **186** and lies above n-type channel region **178** and thick gate dielectric structure **186**. (Thick gate dielectric structure **186** is thicker than thin gate dielectric structure **168**.) CMOS structure **100** also includes a sidewall spacer **188** that touches and laterally surrounds gate **187**.

The combination of n-type body region **175**, n-type channel region **176**, n-type below-the-channel region **178**, p-type source **180**, p-type drain **181**, thick gate dielectric structure **186**, conductive gate **187**, and sidewall spacer **188** define a thick gate dielectric (I/O) PMOS transistor **190**. Thus, dual gate dielectric CMOS structure **100** includes the NMOS transistors **133** and **150** and the PMOS transistors **172** and **190**.

In the present example, the p-type body regions **116** and **135** each has a maximum depth **D1** that is less than a maximum depth **D2** of each of the n-type body regions **155** and **175** and each of the n-type extension regions **142** and **144**. (Alternately, the p-type body regions **116** and **135** can each have a maximum depth that is greater than the maximum depth of each of the n-type body regions **155** and **175** and each of the n-type extension regions **142** and **144**.)

Further, the p-type extension regions **182** and **184** each has a maximum depth **D3** that is less than the maximum depth **D1** of each of the p-type body regions **116** and **135**. In addition, the p-type body regions **116** and **135** are spaced apart from each other, while the n-type body regions **155** and **175** are spaced apart from each other.

With respect to core NMOS transistor **133**, when a positive drain-to-source voltage V_{DS} is present, and the gate-to-source voltage V_{GS} is more positive than the threshold voltage, NMOS transistor **133** turns on and electrons flow from source region **120** to drain region **121**. When the gate-to-source voltage V_{GS} is more negative than the threshold voltage, core NMOS transistor **133** turns off and no electrons (other than a very small leakage current) flow from source region **120** to drain region **121**.

Similarly, with respect to I/O NMOS transistor **150**, when a positive drain-to-source voltage V_{DS} is present, and the gate-to-source voltage V_{GS} is more positive than the threshold voltage, NMOS transistor **150** turns on and electrons flow from source region **140** to drain region **141**. When the gate-to-source voltage V_{GS} is more negative than the threshold voltage, I/O NMOS transistor **150** turns off and no electrons (other than a very small leakage current) flow from source region **140** to drain region **142**. The threshold voltage of NMOS transistor **133** is less than the threshold voltage of NMOS transistor **150**.

With respect to core PMOS transistor **172**, when a negative drain-to-source voltage V_{DS} is present, and the gate-to-source voltage V_{GS} is more negative than the threshold voltage, PMOS transistor **172** turns on and holes flow from source region **160** to drain region **161**. When the gate-to-source voltage V_{GS} is more positive than the threshold voltage, PMOS transistor **172** turns off and no holes (other than a very small leakage current) flow from source region **160** to drain region **161**.

Similarly, with respect to I/O PMOS transistor **190**, when a negative drain-to-source voltage V_{DS} is present, and the gate-to-source voltage V_{GS} is more negative than the threshold voltage, PMOS transistor **190** turns on and holes flow

from source region **180** to drain region **181**. When the gate-to-source voltage V_{GS} is more positive than the threshold voltage, PMOS transistor **190** turns off and no holes (other than a very small leakage current) flow from source region **180** to drain region **181**.

In addition, the core NMOS and PMOS transistors **133** and **172** can utilize a power supply voltage of 1.2V, while the I/O NMOS and PMOS transistors **150** and **190** can utilize a power supply voltage of 1.5V. The NMOS transistors **133** and **150** and the PMOS transistors **172** and **190** can also operate with other power supply voltages as well. For example, the core NMOS and PMOS transistors **133** and **172** can utilize a power supply voltage of 3.3V, while the I/O NMOS and PMOS transistors **150** and **190** can utilize a power supply voltage of 5.0V. (The halos **126**, **127**, **166**, and **167** can be omitted in higher-voltage applications.)

FIGS. **2A-2L** illustrate an example of a method **200** of forming a dual gate dielectric CMOS structure in accordance with the present invention. FIG. **2A** shows a flow chart of method **200**, while FIGS. **2B-2L** show cross-sectional views of method **200**. In the present example, method **200** forms the NMOS and PMOS transistors of a core CMOS circuit and the NMOS and PMOS transistors of an I/O CMOS circuit.

As shown in FIG. **2A**, method **200** begins at step **202-1** by forming a trench isolation structure in a conventionally-formed substrate (e.g., single-crystal silicon with a p-type conductivity and a resistance of 2-12 ohm-cm). For example, a trench isolation structure can be formed by first depositing an isolation stack (e.g., 100 Å of SiO₂ followed by 2000 Å of Si₃N₄) on the substrate, followed by selectively etching a trench through the isolation stack and into the substrate.

The trench can be selectively etched by first forming a patterned photoresist layer on the isolation stack in a conventional manner, which includes depositing a layer of photoresist, projecting a light through a patterned black/clear glass plate known as a mask to form a patterned image on the layer of photoresist, and removing the imaged photoresist regions, which were softened by exposure to the light.

Once the patterned photoresist layer has been formed, the exposed region of the isolation stack and underlying portion of the substrate are etched in a conventional fashion to form a trench approximately 3500 Å-5000 Å deep in the wafer. The patterned photoresist layer is then removed using standard processes, such as an ash process.

Following this, an isolation material (e.g., one or more different oxides) is deposited on the isolation stack to fill up the trench. After the trench has been filled, the isolation material is planarized (e.g., using chemical-mechanical polishing), stopping on the top surface of the isolation stack (e.g., the top surface of the Si₃N₄), to form a trench isolation structure that extends into the substrate.

Next, all or a portion of the isolation stack is removed. In the present example, a portion of the isolation stack is removed (e.g., the top Si₃N₄ layer of the isolation stack can be removed with hot H₃PO₄), leaving a remaining isolation stack. FIG. **2B** shows method **200** after a portion of the isolation stack has been removed, and includes a p-type substrate **212**, a trench isolation structure **214** that touches substrate **212**, and a remaining isolation stack **215**.

As shown in FIG. **2A**, after all or a portion of the isolation stack has been removed, method **200** next moves to step **202-2** to form an n-type core well, an n-type source extension well, an n-type drain extension well, and an n-type I/O body well in the substrate. As shown in FIG. **2B**, the n-type

wells can be formed by first forming a patterned photoresist layer **216** in a conventional manner to touch and lie over remaining isolation stack **215**.

After patterned photoresist layer **216** has been formed, donor-type (n-type) impurity atoms, such as phosphorous or arsenic, are implanted into p-type substrate **212** with multiple implant energies (chain implants) in a conventional manner. The n-type implant forms an n-type core well **217**, an n-type source extension well **218**, an n-type drain extension well **219**, and an n-type I/O body well **220** that each touches p-type substrate **212**.

As a result of being simultaneously formed, the n-type wells **217**, **218**, **219**, and **220** each has substantially the same maximum depth and the same dopant profile. Further, the upper regions of the n-type wells **217**, **218**, **219**, and **220** have the same average dopant concentration, which is selected for n-type well **220** to set the threshold voltage of a to-be-formed PMOS transistor for the I/O CMOS circuit. Following the implant, patterned photoresist layer **216** is removed in a conventional fashion.

As shown in FIG. **2A**, method **200** next moves to step **202-3** to form a p-type core well, a p-type I/O body well, a p-type source extension well, and a p-type drain extension well in the substrate. As shown in FIG. **2C**, the p-type wells can be formed by first forming a patterned photoresist layer **222** in a conventional manner to touch and lie over remaining isolation stack **215**, and cover the n-type wells **217**, **218**, **219**, and **220**.

After patterned photoresist layer **222** has been formed, acceptor-type (p-type) dopant atoms, such as boron, are implanted into p-type substrate **212** with multiple implant energies (chain implants) in a conventional fashion. The p-type implant forms a p-type core well **223** and a p-type I/O body well **224** that each touch p-type substrate **212**.

The p-type implant also forms a p-type source extension well **225** and a p-type drain extension well **226** that each touch n-type I/O well **220** and lie spaced apart from p-type substrate **212**. The doses of the p-type chain implants are selected so that the upper portion of n-type well **220** is converted into a net acceptor-type region to form the p-type source extension well **225** and drain extension well **226**, while the lower portion of n-type well **220** remains a net donor-type region. (The dose of the deeper p-type implants can be set to form net acceptor-type regions below the net donor-type regions that lie below p-type source extension well **225** and p-type drain extension well **226** if required by p-type core well **223** and p-type I/O body well **224** as long as the net donor-type regions sufficiently isolate p-type source extension well **225** and p-type drain extension well **226**.)

In the present example, the maximum depths of the p-type wells **223**, **224**, **225**, and **226** are each less than the maximum depths of the n-type wells **217**, **218**, **219**, and **220**. (Alternately, the maximum depths of the p-type wells **223**, **224**, **225**, and **226** can each be greater than the maximum depths of the n-type wells **217**, **218**, **219**, and **220**.)

As a result of being simultaneously formed, the p-type wells **223** and **224** each has substantially the same maximum depth and the same dopant profile. Although formed at the same time, the p-type wells **225** and **226** (the regions with net acceptor-type impurity atoms) have a shallower maximum depth than the p-type wells **223** and **224** because the p-type wells **225** and **226** are formed in n-type well **220**. Further, the upper regions of the p-type wells **223** and **224** have the same average dopant concentration, which is selected for p-type well **224** to set the threshold voltage of a to-be-formed NMOS transistor for the I/O CMOS circuit.

(The upper regions of the p-type wells **223**, **224**, **225**, and **226** have the same average concentration of acceptor-type impurity atoms.)

Further, n-type well **220** includes an n-type channel region **220-1** that lies between the p-type wells **225** and **226**, and an n-type below-the-channel region **220-2** that touches and lies below channel region **220-1**. Channel region **220-1** has an average dopant concentration, while below-the-channel region **220-2** has a dopant profile. Channel region **220-1** also has a middle point **220-3** that lies mid-way between p-type well **225** and p-type well **226**. A channel region is the surface portion of the well that influences the threshold voltage of the transistor.

In addition, p-type well **224** includes a p-type channel region **224-1** that lies between the n-type wells **218** and **219**, and a p-type below-the-channel region **224-2** that touches and lies below channel region **224-1**. Channel region **224-1** has an average dopant concentration, while below-the-channel region **224-2** has a dopant profile. Channel region **224-1** also has a middle point **224-3** that lies mid-way between n-type well **218** and n-type well **219**.

Following the implant, patterned photoresist layer **222** is removed in a conventional fashion. After patterned photoresist layer **222** has been removed, the n-type wells **217**, **218**, **219**, and **220**, and the p-type wells **223**, **224**, **225**, and **226** are driven in (e.g., annealed at 1100° C. in a neutral ambient such as N₂).

As shown in FIG. 2A, after the p-type core well, the p-type I/O body well, the p-type source extension well, and the p-type drain extension well have been formed, method **200** next moves to step **202-4** to form a thin gate dielectric layer on the n-type and p-type core wells, and a thick gate dielectric layer on the n-type source extension well, the p-type I/O body well, the n-type drain extension well, the p-type source extension well, the n-type I/O body well, and the p-type drain extension well.

As shown in FIG. 2D, the thin and thick gate dielectric layers can be formed by first removing remaining isolation stack **215**, followed by a conventional cleaning process to prepare the top surfaces of the wells **217**, **218**, **219**, **220**, **223**, **224**, **225**, and **226** for thermal oxide growth. Following this, a gate dielectric structure **228-1** is grown on well **223**, a gate dielectric structure **229-1** is grown on well **217**, a gate dielectric structure **230** is grown on the wells **218**, **219**, and **224**, and a gate dielectric structure **231** is grown on the wells **220**, **225**, and **226**. The gate dielectric layers **228-1**, **229-1**, **230**, and **231** are simultaneously formed. The growth continues until the thicknesses of the gate dielectric structures **228-1**, **229-1**, **230**, and **231** reach the thickness required by the NMOS and PMOS transistors in the I/O CMOS circuits (e.g., 75 Å-200 Å).

As shown in FIG. 2E, once the required thickness has been reached, the growth is stopped and a patterned photoresist layer **232** is formed in a conventional manner to touch and protect the gate dielectric structures **230** and **231**. After patterned photoresist layer **232** has been formed, the gate dielectric structures **228-1** and **229-1** are removed to re-expose the top surfaces of the wells **217** and **223**. Following this, a conventional cleaning process is used to prepare the top surfaces of the wells **217** and **223** for thermal oxide growth.

Next, a gate dielectric structure **228-2** is grown on well **223** and a gate dielectric structure **229-2** is grown on well **217** at the same time. The growth continues until the thicknesses of the gate dielectric structures **228-2** and **229-2** reach the thickness required by the NMOS and PMOS transistors in the core CMOS circuits (e.g., 15 Å-30 Å).

Once the required thickness has been reached, the growth is stopped and patterned photoresist layer **232** is then removed in a conventional fashion.

As shown in FIG. 2A, after the thin and thick gate dielectric structures have been formed, method **200** next moves to step **202-5** to form gate structures on the thin and thick gate dielectric structures. As shown in FIG. 2F, the gate structures can be formed by first depositing a polycrystalline silicon layer **233** approximately 1500 Å thick on the gate dielectric structures **228-2**, **229-2**, **230**, and **231** in a conventional fashion. Following this, a patterned photoresist layer **234** is formed in a conventional manner to touch polycrystalline silicon layer **233**.

Next, as shown in FIG. 2G, the exposed regions of polycrystalline silicon layer **233** are etched in a conventional fashion to form a gate that touches gate dielectric structure **228**, a gate that touches gate dielectric structure **229**, a gate that touches gate dielectric structure **230**, and a gate that touches gate dielectric structure **231**. After the gate structures **235**, **236**, **237**, and **238** have been formed, patterned photoresist layer **234** is removed in a conventional manner.

The exposed surfaces of the gates are then oxidized to form a gate structure **235** that touches gate dielectric structure **228**, a gate structure **236** touches gate dielectric structure **229**, a gate structure **237** touches gate dielectric structure **230**, and a gate structure **238** that touches gate dielectric structure **231**. The gate structures **237** and **238** are formed to have a length L1 and L2, respectively, which are longer (e.g., 10×) than the lengths L3 and L4 of the gate structures **235** and **236**, respectively. At this point, a thin offset spacer can be optionally formed by depositing a thin non-conductive layer, and then anisotropically etching the thin non-conductive layer to form the offset spacer.

As shown in FIG. 2A, after the gate structures have been formed, method **200** next moves to step **202-6** to form a core n-type source extension region and a core n-type drain extension region. As shown in FIG. 2H, the core n-type source and drain extension regions can be formed by first forming a patterned photoresist layer **249** in a conventional manner. Patterned photoresist layer **249** touches the gate structures **236**, **237**, and **238**, and overlies to protect the n-wells **217**, **218**, **219**, and **220** and the p-wells **224**, **225**, and **226**.

When patterned photoresist layer **249** is formed, the wells **223** and **224** include the acceptor-type impurity atoms. In addition, the wells **223** and **224** are substantially free of the donor-type impurity atoms, and have substantially identical dopant profiles. Further, the wells **217** and **220** include the donor-type impurity atoms. In addition, the wells **217** and **220** are substantially free of the acceptor-type impurity atoms, and have substantially identical dopant profiles.

After patterned photoresist layer **249** has been formed, donor-type (n-type) impurity atoms are implanted through an opening in patterned photoresist layer **249** into p-type well **223** in a conventional manner. The n-type implant forms an n-type source extension region **250** and an n-type drain extension region **251** in p-type well **223**.

The implant also defines a p-type channel region **252** that lies between n-type source extension region **250** and an n-type drain extension region **251**, and a p-type below-the-channel region **253** of p-type well **223** that touches and lies below p-type channel region **252**. P-type channel region **252**, in turn, has a middle point **254** that lies mid-way between the extension regions **250** and **251**. P-type channel region **252** at middle point **254** includes the acceptor-type of impurity atoms. In addition, p-type channel region **252** at

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middle point **254** is substantially free of the donor-type of impurity atoms, and has an average dopant concentration.

As shown in FIG. 2A, after the n-type core source extension region and the n-type core n-type drain extension region have been formed, method **200** next moves to step **202-7** to set the threshold voltage of the core NMOS transistor. As shown in FIG. 2H, the threshold voltage of the core NMOS transistor can be set by implanting acceptor-type (p-type) dopant atoms through the opening in layer **249** into p-type well **223** in a conventional fashion to increase the average dopant concentration of p-type channel region **252**.

The implant energy of the p-type implant is selected to penetrate through gate structure **235** into p-type well **223**. The dose is selected (in combination with the dopant concentration of any to-be-formed p-type halos) to set the threshold voltage of a to-be-formed NMOS transistor for the core CMOS circuit by raising the concentration of acceptor-type impurity atoms in channel region **252**.

Thus, due to the implantation of p-type dopant atoms, p-type channel region **252** has a higher average dopant concentration at middle point **254** than the average dopant concentration of channel region **224-1** at middle point **224-3**. However, because the dopant profiles of the p-type wells **223** and **224** were initially the same, the dopant profiles of below-the-channel region **224-2** and below-the-channel region **253** remain substantially identical.

One of the advantages of the present invention is the p-type implant used to adjust the threshold voltage of the to-be-formed core NMOS transistor is additive, i.e., the p-type implant raises the concentration of p-type atoms that are present at the top surface of p-type well **223**. This, in turn, leads to less variation in the threshold voltage when compared to the counter doping of one of the prior art approaches. Further, the p-type dopant is implanted through thin gate dielectric structure **228-2**, which requires less implant energy and therefore results in less threshold voltage variation.

Next, as shown in FIG. 2H, the threshold voltage of the core NMOS transistor is further set by forming source and drain halos for the core NMOS transistor. The source and drain halos for the core NMOS transistor can be formed by again implanting acceptor-type impurity atoms through the opening in layer **249**, this time at a number of angles to form a p-type halo **255** and a p-type halo **256** in p-type well **223**. Gate structure **235** blocks the halo implants. As a result, the angled implants allow the halos **255** and **256**, which have higher dopant concentrations than the adjoining portions of below-the-channel region **253**, to extend under the ends of gate structure **235**.

Another of the advantages of the present invention is the p-type implant used to adjust the threshold voltage of the to-be-formed core NMOS transistor reduces the dose required to form the halos **255** and **256**, which results in better transistor performance. (The halos **255** and **256** can optionally be omitted.) After the p-type halos **255** and **256** have been formed, patterned photoresist layer **249** is removed in a conventional fashion. (The order that the impurity atoms are implanted can be reversed or otherwise altered.)

As shown in FIG. 2A, after the threshold voltage for core NMOS transistor has been set, method **200** next moves to step **202-8** to form a core p-type source extension region and a core p-type drain extension region. As shown in FIG. 2I, the core p-type source and drain regions can be formed by first forming a patterned photoresist layer **257** in a conventional manner. Patterned photoresist layer **257** touches the

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gate structures **235**, **237**, and **238**, and overlies to protect the n-wells **218**, **219**, and **220** and the p-wells **223**, **224**, **225**, and **226**.

After patterned photoresist layer **257** has been formed, acceptor-type (p-type) impurity atoms are implanted through an opening in layer **257** into n-type well **217** in a conventional manner. The p-type implant forms a p-type source extension region **258** and a p-type drain extension region **259** in n-type well **217**.

The implant also defines an n-type channel region **260** that lies between the p-type source and drain extension regions **258** and **259**, and an n-type below-the-channel region **261** of n-type well **217** that touches and lies below n-type channel region **260**. N-type channel region **260**, in turn, has a middle point **262** that lies mid-way between the extension regions **258** and **259**.

As shown in FIG. 2A, after the core p-type source extension region and the core p-type drain extension region have been formed, method **200** next moves to step **202-9** to set the threshold voltage of the core PMOS transistor. As shown in FIG. 2I, the threshold voltage of the core PMOS transistor can be set by implanting donor-type (n-type) impurity atoms through the opening in layer **257** into n-type well **217** in a conventional fashion to increase the average dopant concentration of n-type channel region **260**.

The implant energy of the n-type implant is selected to penetrate through gate structure **236** into n-type well **217**. The dose is selected (in combination with the dopant concentration of any to-be-formed n-type halos) to set the threshold voltage of a to-be-formed core PMOS transistor in n-type well **217** by raising the concentration of donor-type impurity atoms in channel region **260**.

Thus, due to the implantation of n-type dopant atoms, n-type channel region **260** has a higher average dopant concentration at middle point **262** than the average dopant concentration of channel region **220-1** at middle point **220-3**. However, because the dopant profiles of the n-type wells **217** and **220** were initially the same, the dopant profiles of below-the-channel region **220-2** and below-the-channel region **261** remain substantially identical.

One of the advantages of the present invention is the n-type implant used to adjust the threshold voltage of the to-be-formed core PMOS transistor is additive, i.e., the n-type implant raises the concentration of n-type atoms that are present in channel region **260**. This, in turn, leads to less variation in the threshold voltage when compared to the counter doping of one of the prior art approaches. Further, the n-type dopant is implanted through thin gate dielectric structure **229**, which requires less implant energy and therefore results in less threshold voltage variation.

Next, as shown in FIG. 2I, the threshold voltage of the core PMOS transistor is further set by forming source and drain halos for the core PMOS transistor. The source and drain halos for the core PMOS transistor can be formed by again implanting the donor-type impurity atoms through the opening in layer **257**, this time at a number of angles to form an n-type halo **263** and an n-type halo **264** in n-type well **217**. Gate structure **236** blocks the halo implants. As a result, the angled implants allow the halos **263** and **264**, which have higher dopant concentrations than the adjoining portions of below-the-channel region **261**, to extend under the ends of gate structure **236**.

Another of the advantages of the present invention is the n-type implant used to adjust the threshold voltage of the to-be-formed core PMOS transistor reduces the dose

required to form the halos **263** and **264**, which results in better transistor performance. (The halos **263** and **264** can optionally be omitted.)

After the n-type halos **263** and **264** have been formed, patterned photoresist layer **257** is removed in a conventional fashion. (The order that the impurity atoms are implanted can be reversed or otherwise altered.) After patterned photoresist layer **257** has been removed, the extension regions **250**, **251**, **258**, and **259**, the halos **255**, **256**, **263**, and **264**, and the implants into channel regions **252** and **260** are driven in (e.g., annealed at 1100° C. in a neutral ambient such as N₂).

As shown in FIG. 2A, after the threshold voltage of the core PMOS transistor has been set, method **200** next moves to step **202-10** to form side wall spacers. As shown in FIG. 2J, the side wall spacers can be formed by depositing a non-conductive layer in a conventional manner to touch the gate dielectric structures **228**, **229**, **230**, and **231**, and the gate structures **235**, **236**, **237**, and **238**. The non-conductive layer can be implemented with, for example, an oxide layer.

Following this, the non-conductive layer is anisotropically etched to form a side wall spacer **265** that laterally surrounds gate structure **235**, a side wall spacer **266** that laterally surrounds gate structure **236**, a side wall spacer **267** that laterally surrounds gate structure **237**, and a side wall spacer **268** that laterally surrounds gate structure **238**.

As shown in FIG. 2A, after the side wall spacers have been formed, method **200** next moves to step **202-11** to form n+ source and drain regions for the core and I/O NMOS transistors. As shown in FIG. 2K, the n+ source and drain regions for the core and I/O NMOS transistors can be formed by first forming a patterned photoresist layer **270** in a conventional fashion.

Patterned photoresist layer **270** touches gate structures **236** and **238**, and overlies to protect the n-type wells **217** and **220** and the p-type wells **225** and **226**. After patterned photoresist layer **270** has been formed, donor-type impurity atoms are conventionally implanted through an opening in layer **270** into p-type well **223** and the n-type wells **218** and **219**.

The implant forms an n+ source region **272** that touches source extension region **250**, and an n+ drain region **274** that touches drain extension region **251**. The implant also forms an n+ source region **276** that touches n-type well **218**, and an n+ drain region **278** that touches n-type well **219**. Following this, patterned photoresist layer **270** is removed in a conventional manner.

As shown in FIG. 2A, after the n+ source and drain regions for the core and I/O NMOS transistors have been formed, method **200** next moves to step **202-12** to form p+ source and drain regions for the core and I/O PMOS transistors. As shown in FIG. 2L, the p+ source and drain regions for the core and I/O NMOS transistors can be formed by first forming a patterned photoresist layer **280** in a conventional fashion.

Patterned photoresist layer **280** touches gate structures **235** and **237**, and overlies to protect the p-type wells **223** and **224** and the n-wells **218** and **219**. After patterned photoresist layer **280** has been formed, acceptor-type impurity atoms are conventionally implanted through an opening in layer **280** into n-type well **217**, p-type well **225**, and p-type well **226**.

The implant forms a p+ source region **282** that touches source extension region **258**, and a p+ drain region **284** that touches drain extension region **259**. The implant also forms a p+ source region **286** that touches p-type well **225**, and a

p+ drain region **288** that touches p-type well **226**. Following this, patterned photoresist layer **280** is removed in a conventional manner.

After the n+ source regions **272** and **276**, the n+ drain regions **274** and **278**, the p+ source region **282** and **286**, and the p+ drain regions **284** and **288** have been formed, the n+ source regions **272** and **276**, the n+ drain regions **274** and **278**, the p+ source region **282** and **286**, and the p+ drain regions **284** and **288** are driven in (e.g., annealed at 1100° C. in a neutral ambient such as N₂). Method **200** then continues with conventional steps to complete the formation of the CMOS structure.

None of the drive ins are sufficient to cause acceptor-type impurity atoms from p-type source **258/282** and p-type drain **259/284** to diffuse over to the middle point **262** of n-type channel region **260**. As a result, n-type channel region **260** at the middle point **262** is substantially free of acceptor-type impurity atoms.

Further, none of the drive ins are sufficient to cause acceptor-type impurity atoms from p-type source **225/286** and p-type drain **226/288** to diffuse over to the middle point **220-3** of n-type channel region **220-1**. As a result, n-type channel region **220-1** at the middle point **220-3** is substantially free of acceptor-type impurity atoms.

None of the drive ins are sufficient to cause donor-type impurity atoms from n-type source **250/272** and n-type drain **251/274** to diffuse over to the middle point **254** of p-type channel region **252**. As a result, p-type channel region **252** at the middle point **254** is substantially free of donor-type impurity atoms.

Similarly, none of the drive ins are sufficient to cause donor-type impurity atoms from n-type source **218/276** and n-type drain **219/278** to diffuse over to the middle point **224-3** of p-type channel region **224-1**. As a result, p-type channel region **224-1** at the middle point **224-3** is substantially free of donor-type impurity atoms.

P-type well **223**, p-type channel region **252**, p-type below-the-channel region **253**, p-type halo **255**, p-type halo **256**, n-type source **250/272**, n-type drain **251/274**, gate dielectric structure **228**, gate structure **235**, and sidewall spacer **265** define a core NMOS transistor **290**, which can be used to implement NMOS transistor **133**.

Further, n-type well **217**, n-type channel region **260**, n-type below-the-channel region **261**, n-type halo **263**, n-type halo **264**, p-type source **258/282**, p-type drain **259/284**, gate dielectric structure **229**, gate structure **236**, and sidewall spacer **266** define a core PMOS transistor **292**, which can be used to implement PMOS transistor **172**.

In addition, n-type well **218**, n-type well **219**, p-type well **224**, n-type source **276**, n-type drain **278**, p-type channel region **224-1**, p-type below-the-channel region **224-2**, gate dielectric structure **230**, gate structure **237**, and sidewall spacer **267** define an I/O NMOS transistor **294**, which can be used to implement NMOS transistor **150**.

Further, n-type well **220**, p-type well **225**, p-type well **226**, p-type source **286**, p-type drain **288**, n-type channel region **220-1**, n-type below-the-channel region **220-2**, gate dielectric structure **231**, gate structure **238**, and sidewall spacer **268** define an I/O PMOS transistor **296**, which can be used to implement PMOS transistor **190**. The transistors **290**, **292**, **294**, and **296**, in turn, form a dual gate dielectric CMOS structure **298**.

One of the advantages of the present invention is that the present invention eliminates the need to use two patterned photoresist layers to form the source and drain extension regions for the NMOS and PMOS transistors in the I/O CMOS circuits. The elimination of the two patterned pho-

toresist layers, and the reticles that are required to form them, significantly reduces the cost required to form a dual gate dielectric CMOS structure.

FIG. 3 shows a cross-sectional view that illustrates an example of a dual gate dielectric CMOS structure 300 in accordance with an alternate embodiment of the present invention. CMOS structure 300 is similar to CMOS structure 100 and, as a result, utilizes the same reference numerals to designate the elements which are common to both structures.

As shown in FIG. 3, CMOS structure 300 differs from CMOS structure 100 in that base structure 110 utilizes a p-type body region 310 in lieu of p-type body region 135. CMOS structure 300 also differs from CMOS structure 100 in that n-type source 140 utilizes an n-type source extension region 312 in lieu of n-type source extension region 142, and n-type drain 141 utilizes an n-type drain extension region 314 in lieu of n-type drain extension region 144.

P-type body region 310, in turn, includes a p-type channel region 320, a middle point 322 of channel region 320, and a p-type below-the-channel region 324 that touches and lies directly below p-type channel region 320. P-type channel region 320 at the middle point 322 is substantially free of donor-type impurity atoms.

In addition, p-type channel region 320 has a channel length L2 that is substantially greater (e.g., 10X) than the channel length L1 of p-type channel region 117, and an average dopant concentration that is substantially less than the average dopant concentration of p-type channel region 117. In addition, p-type below-the-channel region 324 has a dopant profile directly below middle point 322 that is substantially identical to the dopant profile of p-type below-the-channel region 119 directly below middle point 118.

Base structure 110 can also optionally include a p-type halo 330 that touches p-type body region 310 and n-type source 140, and a p-type halo 332 that touches p-type body region 310 and n-type drain 141. The p-type halos 330 and 332, which are spaced apart, have higher average dopant concentrations than the adjoining portions of below-the-channel region 324. (The halos 330 and 332 can be omitted in high-voltage applications.)

The combination of p-type body region 310, p-type channel region 320, p-type below-the-channel region 324, n-type source 140 (including source extension region 312), n-type drain 141 (including drain extension region 314), p-type halo 330, p-type halo 332, thick gate dielectric structure 146, conductive gate 147, and sidewall spacer 148 define a thick gate dielectric (I/O) NMOS transistor 340.

As further shown in FIG. 3, CMOS structure 300 also differs from CMOS structure 100 in that base structure 110 utilizes an n-type body region 350 in lieu of n-type body region 175. CMOS structure 300 also differs from CMOS structure 100 in that p-type source 180 utilizes a p-type source extension region 352 in lieu of p-type source extension region 182, and p-type drain 181 utilizes a p-type drain extension region 354 in lieu of p-type drain extension region 184.

N-type body region 350, in turn, includes an n-type channel region 360, a middle point 362 of channel region 360, and an n-type below-the-channel region 364 that touches and lies directly below n-type channel region 360. N-type channel region 360 at the middle point 362 is substantially free of acceptor-type impurity atoms.

In addition, n-type channel region 360 has a channel length L4 that is substantially greater (e.g., 10x) than the channel length L3 of n-type channel region 156, and an average dopant concentration that is substantially less than

the average dopant concentration of n-type channel region 156. In addition, n-type below-the-channel region 364 has a dopant profile directly below middle point 362 that is substantially identical to the dopant profile of n-type below-the-channel region 158 directly below middle point 157.

Base structure 110 can also optionally include an n-type halo 370 that touches n-type body region 350 and p-type source 180, and an n-type halo 372 that touches n-type body region 350 and p-type drain 181. The n-type halos 370 and 372, which are spaced apart, have higher average dopant concentrations than the adjoining portions of below-the-channel region 364. (The halos 370 and 372 can be omitted in high-voltage applications.)

The combination of n-type body region 350, n-type channel region 360, n-type below-the-channel region 364, p-type source 180 (including source extension region 352), p-type drain 181 (including drain extension region 354), n-type halo 370, n-type halo 372, thick gate dielectric structure 186, conductive gate 187, and sidewall spacer 188 define a thick gate dielectric (I/O) NMOS transistor 380.

In the present example, each of the body regions 116, 155, 310, 350 has substantially the same depth D. (Alternately, the p-type body regions 116 and 310 can have a greater or lesser maximum depth than the n-type body regions 155 and 350.) Further, the p-type body regions 116 and 310 are spaced apart from each other, while n-type body regions 155 and 350 are spaced apart from each other. NMOS transistor 340 operates substantially the same as NMOS transistor 150, while PMOS transistor 380 operate substantially the same as PMOS transistor 190.

FIGS. 4A-4I illustrate an example of a method 400 of forming a dual gate dielectric CMOS structure in accordance with an alternate embodiment of the present invention. FIG. 4A shows a flow chart of method 400, while FIGS. 4B-4I show cross-sectional views of method 400. In the present example, method 400 forms the NMOS and PMOS transistors of a core CMOS circuit and the NMOS and PMOS transistors of an I/O CMOS circuit.

Method 400 begins the same as method 200 and, as a result, utilizes the same reference numeral to designate the step that is common to both methods. As shown in FIG. 4A, method 400 also begins with step 202-1, which is the formation of a trench isolation structure. As shown in FIG. 4B, method 400 utilizes a p-type substrate 412, and forms a trench isolation structure 414 in substrate 412. In the present example, method 400 also leaves a remaining isolation stack.

As further shown in FIG. 4A, after the trench isolation structure has been formed (e.g., after all or a portion of the isolation stack has been removed), method 400 next moves to step 402-2 to form an n-type core well and an n-type I/O well in the substrate. The n-type wells can be formed in a similar manner to the formation of n-type well 217 by first forming a patterned photoresist layer in a conventional manner to touch and lie over the remaining isolation stack.

After the patterned photoresist layer has been formed, donor-type (n-type) impurity atoms, such as phosphorous or arsenic, are implanted into the p-type substrate with multiple implant energies (chain implants) in a conventional manner. As shown in FIG. 4B, the n-type implant forms an n-type core well 418 and an n-type I/O well 420 that each touches p-type substrate 412.

As a result of being simultaneously formed, the n-type wells 418 and 420 each has substantially the same maximum depth and the same dopant profile. Further, the upper regions of the n-type wells 418 and 420 have the same average dopant concentration, which is selected (in combination

with the dopant concentration of any to-be-formed n-type halos) for n-type well **420** to set the threshold voltage of a to-be-formed PMOS transistor for the I/O CMOS circuit. Following the implant, the patterned photoresist layer is removed in a conventional fashion.

As shown in FIG. 4A, method **400** next moves to step **402-3** to form a p-type core well and a p-type I/O well in the substrate. The p-type wells can be formed in a similar manner to the formation of p-type well **223** by first forming a patterned photoresist layer in a conventional manner to touch and lie over the remaining isolation stack, and cover the n-type wells **418** and **420**.

After the patterned photoresist layer has been formed, acceptor-type (p-type) dopant atoms, such as boron, are implanted into the p-type substrate with multiple implant energies (chain implants) in a conventional fashion. As shown in FIG. 4B, the p-type implant forms a p-type core well **422** and a p-type I/O well **424** that each touch p-type substrate **412**.

As a result of being simultaneously formed, the p-type wells **422** and **424** each has substantially the same maximum depth and the same dopant profile. Further, the upper regions of the p-type wells **422** and **424** have the same average dopant concentration, which is selected (in combination with the dopant concentration of any to-be-formed p-type halos) for p-type well **424** to set the threshold voltage of a to-be-formed NMOS transistor for the I/O CMOS circuit. Following the implant, the patterned photoresist layer is removed in a conventional fashion. After the patterned photoresist layer has been removed, the n-type wells **418** and **420**, and the p-type wells **422** and **424** are driven in (e.g., annealed at 1100° C. in a neutral ambient such as N₂).

As shown in FIG. 4A, after the p-type core well and the p-type I/O well have been formed, method **400** next moves to step **402-4** to form a thin gate dielectric layer on the n-type and p-type core wells, and a thick gate dielectric layer on the n-type and p-type I/O wells. The thin and thick gate dielectric layers can be formed in a similar manner to the formation of the thin and thick gate dielectric layers **228-2**, **229-2**, **231**, and **232** by first removing the remaining isolation stack, followed by a conventional cleaning process to prepare the top surfaces of the wells **418**, **420**, **422**, and **424** for thermal oxide growth.

Following this, a gate dielectric structure is grown on well **422**, a gate dielectric structure is grown on well **418**, a gate dielectric structure **425** is grown on well **424**, and a gate dielectric structure **426** is grown on well **420**. The gate dielectric structures are simultaneously formed. The growth continues until the thicknesses of the gate dielectric structures reach the thickness required by the NMOS and PMOS transistors in the I/O CMOS circuits (e.g., 75 Å-200 Å).

Once the required thickness has been reached, the growth is stopped and a patterned photoresist layer is formed in a conventional manner to touch and protect the gate dielectric structures **425** and **426**. After the patterned photoresist layer has been formed, the gate dielectric structures grown on the wells **418** and **422** are removed to re-expose the top surfaces of the wells **418** and **422**. Following this, a conventional cleaning process is used to prepare the top surfaces of the wells **418** and **422** for thermal oxide growth.

Next, a gate dielectric structure **427** is grown on well **422** and a gate dielectric structure **428** is grown on well **418** at the same time. The growth continues until the thicknesses of the gate dielectric structures **427** and **428** reach the thickness required by the NMOS and PMOS transistors in the core CMOS circuits (e.g., 15 Å-30 Å). Once the required thick-

ness has been reached, the growth is stopped and the patterned photoresist layer is then removed in a conventional fashion.

As shown in FIG. 4A, after the thin and thick gate dielectric structures have been formed, method **400** next moves to step **402-5** to form gate structures on the thin and thick gate dielectric structures. The gate structures can be formed in a similar manner to the formation of the gate structures **235**, **236**, **237**, and **238** by first depositing a polycrystalline silicon layer approximately 1500 Å thick on the gate dielectric structures **425**, **426**, **427**, and **428** in a conventional fashion.

Following this, as shown in FIG. 4B, a patterned photoresist layer **431** is formed in a conventional manner to touch the polycrystalline silicon layer. Next, as further shown in FIG. 4B, the exposed regions of the polycrystalline silicon layer are etched in a conventional fashion to form a gate that touches gate dielectric structure **425**, a gate that touches gate dielectric structure **426**, a gate that touches gate dielectric structure **427**, and a gate that touches gate dielectric structure **428**. After the gates have been formed, patterned photoresist layer **431** is removed in a conventional manner.

The exposed surfaces of the gates are then oxidized to form a gate structure **432** that touches gate dielectric structure **427**, a gate structure **433** that touches gate dielectric structure **428**, a gate structure **434** touches gate dielectric structure **425**, and a gate structure **435** that touches gate dielectric structure **426**. The gate structures **434** and **435** are formed to have a length L1 and L2, respectively, which are longer (e.g., 10×) than the lengths L3 and L4 of the gate structures **432** and **433**, respectively. At this point, a thin offset spacer can be optionally formed by depositing a thin non-conductive layer, and then anisotropically etching the thin non-conductive layer to form the offset spacer.

As shown in FIG. 4A, after the gate structures have been formed, method **400** next moves to step **402-6** to form an n-type core source extension region and an n-type core drain extension region. As shown in FIG. 4C, the n-type core source and drain extension regions can be formed by first forming a patterned photoresist layer **436** in a conventional manner. Patterned photoresist layer **436** touches the gate structures **433**, **434**, and **435**, and overlies to protect the n-wells **418** and **420**, and p-well **424**.

When patterned photoresist layer **436** is formed, p-type well **422** includes the acceptor-type impurity atoms. In addition, p-type well **422** is substantially free of the donor-type impurity atoms. Further, the p-type wells **422** and **424** have substantially identical dopant profiles. After patterned photoresist layer **436** has been formed, donor-type (n-type) impurity atoms are implanted through an opening in patterned photoresist layer **436** into p-type well **422** in a conventional manner. The n-type implant forms an n-type core source extension region **437** and an n-type core drain extension region **438** in p-type well **422**.

The implant also defines a p-type channel region **440** that lies between n-type core source extension region **437** and n-type core drain extension region **438**, and a p-type below-the-channel region **441** of p-type well **422** that touches and lies below p-type channel region **440**. P-type channel region **440**, in turn, has an average dopant concentration and a middle point **442** that lies mid-way between the extension regions **437** and **438**. P-type channel region **440** at middle point **442** includes the acceptor-type of impurity atoms. In addition, p-type channel region **440** at middle point **442** is substantially free of the donor-type of impurity atoms. P-type below-the-channel region **441** has a dopant profile directly below middle point **442**.

As shown in FIG. 4A, after the n-type core source extension region and the n-type core n-type drain extension region have been formed, method 400 next moves to step 402-7 to set the threshold voltage of the core NMOS transistor. As shown in FIG. 4C, the threshold voltage of the core NMOS transistor can be set by implanting acceptor-type (p-type) dopant atoms through the opening in layer 436 into p-type well 422 in a conventional fashion to increase the average dopant concentration of p-type channel region 440.

The implant energy of the p-type implant is selected to penetrate through gate structure 432 into p-type well 422. The dose is selected (in combination with the dopant concentration of any to-be-formed p-type halos) to set the threshold voltage of a to-be-formed NMOS transistor for the core CMOS circuit by raising the concentration of acceptor-type impurity atoms in channel region 440.

One of the advantages of the present invention is the p-type implant used to adjust the threshold voltage of the to-be-formed core NMOS transistor is additive, i.e., the p-type implant raises the concentration of p-type atoms that are present at the top surface of p-type well 422. This, in turn, leads to less variation in the threshold voltage when compared to the counter doping approach of one of the prior art approaches. Further, the p-type dopant is implanted through thin gate dielectric structure 427, which requires less implant energy and therefore results in less threshold voltage variation.

Next, as shown in FIG. 4C, the threshold voltage of the core NMOS transistor is further set by forming source and drain halos for the core NMOS transistor. The source and drain halos for the core NMOS transistor can be formed by again implanting acceptor-type impurity atoms through the opening in layer 436, this time at a number of angles to form a p-type halo 443 and a p-type halo 444 in p-type well 422. Gate structure 432 blocks the halo implants. As a result, the angled implants allow the halos 443 and 444, which have higher dopant concentrations than the adjoining portions of below-the-channel region 441, to extend under the ends of gate structure 432.

Another of the advantages of the present invention is the p-type implant used to adjust the threshold voltage of the to-be-formed core NMOS transistor reduces the dose required to form the halos 443 and 444, which results in better transistor performance. (The halos 443 and 444 can optionally be omitted.) After the p-type halos 443 and 444 have been formed, patterned photoresist layer 436 is removed in a conventional fashion. (The order that the impurity atoms are implanted can be reversed or otherwise altered.)

As shown in FIG. 4A, after the threshold voltage for the core NMOS transistor has been set, method 400 next moves to step 402-8 to form a p-type core source extension region and a p-type core drain extension region. As shown in FIG. 4D, the p-type core source and drain extension regions can be formed by first forming a patterned photoresist layer 445 in a conventional manner. Patterned photoresist layer 445 touches the gate structures 432, 434, and 435, and overlies to protect n-well 420 and the p-wells 422 and 424. When patterned photoresist layer 445 is formed, n-type well 418 includes the donor-type impurity atoms. In addition, n-type well 418 is substantially free of the acceptor-type impurity atoms. Further, the n-type wells 418 and 420 have substantially identical dopant profiles.

After patterned photoresist layer 445 has been formed, acceptor-type (p-type) impurity atoms are implanted through an opening in layer 445 into n-type well 418 in a conventional manner. The p-type implant forms a p-type core

source extension region 446 and a p-type core drain extension region 447 in n-type well 418.

The implant also defines an n-type channel region 450 that lies between the p-type core source and drain extension regions 446 and 447, and an n-type below-the-channel region 451 of n-type well 418 that touches and lies below n-type channel region 450. N-type channel region 450, in turn, has an average dopant concentration and a middle point 452 that lies mid-way between the extension regions 446 and 447.

As shown in FIG. 4A, after the core p-type source extension region and the core p-type drain extension region have been formed, method 400 next moves to step 402-9 to set the threshold voltage of the core PMOS transistor. As shown in FIG. 4D, the threshold voltage of the core PMOS transistor can be set by implanting donor-type (n-type) impurity atoms through the opening in layer 445 into n-type well 418 in a conventional fashion to increase the average dopant concentration of n-type channel region 450.

The implant energy of the n-type implant is selected to penetrate through gate structure 433 into n-type well 418. The dose is selected (in combination with the dopant concentration of any to-be-formed n-type halos) to set the threshold voltage of a to-be-formed core PMOS transistor in n-type well 418 by raising the concentration of donor-type impurity atoms in channel region 450.

One of the advantages of the present invention is the n-type implant used to adjust the threshold voltage of the to-be-formed core PMOS transistor is additive, i.e., the n-type implant raises the concentration of n-type atoms that are present in channel region 450. This, in turn, leads to less variation in the threshold voltage when compared to the counter doping approach of one of the prior art approaches. Further, the n-type dopant is implanted through thin gate dielectric structure 428, which requires less implant energy and therefore results in less threshold voltage variation.

Next, as shown in FIG. 4D, the threshold voltage of the core PMOS transistor is further set by forming source and drain halos for the core PMOS transistor. The source and drain halos for the core PMOS transistor can be formed by again implanting the donor-type impurity atoms through the opening in layer 445, this time at a number of angles to form an n-type halo 453 and an n-type halo 454 in n-type well 418. Gate structure 433 blocks the halo implants. As a result, the angled implants allow the halos 453 and 454, which have higher dopant concentrations than the adjoining portions of below-the-channel region 451, to extend under the ends of gate structure 433.

Another of the advantages of the present invention is the n-type implant used to adjust the threshold voltage of the to-be-formed core PMOS transistor reduces the dose required to form the halos 453 and 454, which results in better transistor performance. (The halos 453 and 454 can optionally be omitted.) After the n-type halos 453 and 454 have been formed, patterned photoresist layer 445 is removed in a conventional fashion. (The order that the impurity atoms are implanted can be reversed or otherwise altered.)

As shown in FIG. 4A, after the threshold voltage of the core PMOS transistor has been set, method 400 next moves to step 402-10 to form an n-type I/O source extension region and an n-type I/O drain extension region. As shown in FIG. 4E, the n-type I/O source and drain extension regions can be formed by first forming a patterned photoresist layer 455 in a conventional manner. Patterned photoresist layer 455 touches the gate structures 432, 433, and 435, and overlies to protect the n-wells 418 and 420, and p-well 422.

When patterned photoresist layer 455 is formed, p-type well 424 includes the acceptor-type impurity atoms. In addition, p-type well 424 is substantially free of the donor-type impurity atoms. After patterned photoresist layer 455 has been formed, donor-type (n-type) impurity atoms are implanted through an opening in patterned photoresist layer 455 into p-type well 424 in a conventional manner. The n-type implant forms an n-type source extension region 457 and an n-type drain extension region 458 in p-type well 424.

The implant also defines a p-type channel region 460 that lies between n-type source extension region 457 and n-type drain extension region 458, and a p-type below-the-channel region 461 of p-type well 424 that touches and lies below p-type channel region 460. P-type channel region 460, in turn, has an average dopant concentration and a middle point 462 that lies mid-way between the extension regions 457 and 458. P-type channel region 460 at middle point 462 includes the acceptor-type of impurity atoms. In addition, p-type channel region 460 at middle point 462 is substantially free of the donor-type of impurity atoms. P-type below-the-channel region 461 has a dopant profile directly below middle point 462.

As shown in FIG. 4A, after the n-type I/O source extension region and the n-type I/O n-type drain extension region have been formed, method 400 next moves to step 402-11 to form source and drain halos for the I/O NMOS transistor. As shown in FIG. 4E, the source and drain halos for the I/O NMOS transistor can be formed by implanting acceptor-type impurity atoms through the opening in layer 455 at a number of angles to form a p-type halo 463 and a p-type halo 464 in p-type well 424. Gate structure 434 blocks the halo implants. As a result, the angled implants allow the halos 463 and 464, which have higher dopant concentrations than the adjoining portions of below-the-channel region 461, to extend under the ends of gate structure 434. (The halos 463 and 464 can optionally be omitted.) After the p-type halos 463 and 464 have been formed, patterned photoresist layer 455 is removed in a conventional fashion. (The order that the impurity atoms are implanted can be reversed or otherwise altered.)

Thus, unlike p-type channel region 440, where additional acceptor-type impurity atoms were implanted into p-type channel region 440 to raise the average dopant concentration when patterned photoresist layer 436 was in place, no additional acceptor-type impurity atoms were implanted into p-type channel region 460 when patterned photoresist layer 455 was in place.

FIG. 5 shows a graph that illustrates the boron dopant profile of an NMOS core well below an overlying gate in accordance with the present invention. As shown in FIG. 5, line E1 illustrates the concentration of acceptor-type impurity atoms in core well 422 below gate 432. (Alternately, line E1 can illustrate the concentration of acceptor-type impurity atoms in core well 223 below gate 235.) By comparison, line E2 illustrates the concentration of acceptor-type impurity atoms in a prior art core well below the gate where the core well received the well implants alone (i.e., no through-the-gate core well implants).

As a result, due to the implantation of p-type dopant atoms into p-type channel region 440, p-type channel region 440 at middle point 442 has a higher average dopant concentration than the average dopant concentration of p-type channel region 460 at middle point 462. However, because the dopant profiles of the p-type wells 422 and 424 were initially the same, the dopant profiles of below-the-channel region 441 and below-the-channel region 461 remain substantially identical.

As shown in FIG. 4A, after the source and drain halos for the I/O NMOS transistor has been formed, method 400 next moves to step 402-12 to form a p-type I/O source extension region and a p-type I/O drain extension region. As shown in FIG. 4F, the p-type I/O source and drain regions can be formed by first forming a patterned photoresist layer 465 in a conventional manner. Patterned photoresist layer 465 touches the gate structures 432, 433, and 434, and overlies to protect n-well 418 and the p-wells 422 and 424.

After patterned photoresist layer 465 has been formed, acceptor-type (p-type) impurity atoms are implanted through an opening in layer 465 into n-type well 420 in a conventional manner. The p-type implant forms a p-type source extension region 466 and a p-type drain extension region 467 in n-type well 420.

The implant also defines an n-type channel region 470 that lies between the p-type source and drain extension regions 466 and 467, and an n-type below-the-channel region 471 of n-type well 420 that touches and lies below n-type channel region 470. N-type channel region 470, in turn, has an average dopant concentration and a middle point 472 that lies mid-way between the extension regions 466 and 467.

As shown in FIG. 4A, after the p-type I/O source extension region and the p-type I/O drain extension region have been formed, method 400 next moves to step 402-13 to form source and drain halos for the I/O PMOS transistor. As shown in FIG. 4F, the source and drain halos for the I/O PMOS transistor can be formed by implanting donor-type impurity atoms through the opening in layer 465 at a number of angles to form a p-type halo 473 and a p-type halo 474 in p-type well 420. Gate structure 435 blocks the halo implants. As a result, the angled implants allow the halos 473 and 474, which have higher dopant concentrations than the adjoining portions of below-the-channel region 471, to extend under the ends of gate structure 435. (The halos 473 and 474 can optionally be omitted.) After the p-type halos 473 and 474 have been formed, patterned photoresist layer 465 is removed in a conventional fashion. (The order that the impurity atoms are implanted can be reversed or otherwise altered.)

Thus, unlike n-type channel region 450, where additional donor-type impurity atoms were implanted into n-type channel region 450 to raise the average dopant concentration when patterned photoresist layer 445 was in place, no additional donor-type impurity atoms were implanted into n-type channel region 470 when patterned photoresist layer 465 was in place.

As a result, due to the implantation of n-type dopant atoms into n-type channel region 450, n-type channel region 450 has a higher average dopant concentration at middle point 452 than the average dopant concentration of n-type channel region 470 at middle point 472. However, because the dopant profiles of the n-type wells 418 and 420 were initially the same, the dopant profiles of below-the-channel region 451 and below-the-channel region 471 remain substantially identical.

After patterned photoresist layer 465 has been removed, the extension regions 437, 438, 453, 454, 457, 458, 473, and 474, the halos 443, 444, 453, 454, 463, 464, 473, and 474, and the implants into the channel regions 440 and 450 are driven in (e.g., annealed at 1100° C. in a neutral ambient such as N₂).

As shown in FIG. 4A, after the source and drain halos for the I/O PMOS transistor has been formed, method 400 next moves to step 402-14 to form side wall spacers. As shown in FIG. 4G, the side wall spacers can be formed by depos-

iting a non-conductive layer in a conventional manner to touch the gate dielectric structures **425**, **426**, **427**, and **428**, and the gate structures **432**, **433**, **434**, and **435**. The non-conductive layer can be implemented with, for example, an oxide layer.

Following this, the non-conductive layer is anisotropically etched to form a sidewall spacer **475** that laterally surrounds gate structure **432**, a sidewall spacer **476** that laterally surrounds gate structure **433**, a sidewall spacer **477** that laterally surrounds gate structure **434**, and a sidewall spacer **478** that laterally surrounds gate structure **435**.

As shown in FIG. **4A**, after the side wall spacers have been formed, method **400** next moves to step **202-15** to form n+ source and drain regions for the core and I/O NMOS transistors. As shown in FIG. **4H**, the n+ source and drain regions for the core and I/O NMOS transistors can be formed by first forming a patterned photoresist layer **480** in a conventional fashion.

Patterned photoresist layer **480** touches gate structures **433** and **435**, and overlies to protect the n-type wells **418** and **420**. After patterned photoresist layer **480** has been formed, donor-type impurity atoms are conventionally implanted through an opening in layer **480** into the p-type wells **422** and **424**.

The implant forms an n+ source region **481** that touches source extension region **437**, and an n+ drain region **482** that touches drain extension region **438**. The implant also forms an n+ source region **483** that touches source extension region **457**, and an n+ drain region **484** that touches drain extension region **458**. Following this, patterned photoresist layer **480** is removed in a conventional manner.

As shown in FIG. **4A**, after the n+ source and drain regions for the core and I/O NMOS transistors have been formed, method **400** next moves to step **402-16** to form p+ source and drain regions for the core and I/O PMOS transistors. As shown in FIG. **4I**, the p+ source and drain regions for the core and I/O NMOS transistors can be formed by first forming a patterned photoresist layer **485** in a conventional fashion.

Patterned photoresist layer **485** touches gate structures **432** and **434**, and overlies to protect the p-type wells **422** and **424**. After patterned photoresist layer **485** has been formed, acceptor-type impurity atoms are conventionally implanted through an opening in layer **485** into the n-type wells **418** and **420**.

The implant forms a p+ source region **486** that touches source extension region **446**, and a p+ drain region **487** that touches drain extension region **447**. The implant also forms a p+ source region **488** that touches source extension region **466**, and a p+ drain region **487** that touches drain extension region **467**. Following this, patterned photoresist layer **485** is removed in a conventional manner.

After the n+ source regions **481** and **483**, the n+ drain regions **482** and **484**, the p+ source regions **486** and **488**, and the p+ drain regions **487** and **489** have been formed, the n+ source regions **481** and **483**, the n+ drain regions **482** and **484**, the p+ source regions **486** and **488**, and the p+ drain regions **487** and **489** are driven in (e.g., annealed at 1100° C. in a neutral ambient such as N₂). Method **400** then continues with conventional steps to complete the formation of the CMOS structure.

None of the drive ins are sufficient to cause acceptor-type impurity atoms from p-type source **446/486** and p-type drain **447/487** to diffuse over to the middle point **452** of n-type channel region **450**. As a result, n-type channel region **450** at the middle point **452** is substantially free of acceptor-type impurity atoms.

Also, none of the drive ins are sufficient to cause acceptor-type impurity atoms from p-type source **466/488** and p-type drain **467/489** to diffuse over to the middle point **472** of n-type channel region **470**. As a result, n-type channel region **470** at the middle point **472** is substantially free of acceptor-type impurity atoms.

Further, none of the drive ins are sufficient to cause donor-type impurity atoms from n-type source **437/481** and n-type drain **438/482** to diffuse over to the middle point **442** of p-type channel region **440**. As a result, p-type channel region **440** at the middle point **442** is substantially free of donor-type impurity atoms.

Similarly, none of the drive ins are sufficient to cause donor-type impurity atoms from n-type source **457/483** and n-type drain **458/484** to diffuse over to the middle point **462** of p-type channel region **460**. As a result, p-type channel region **460** at the middle point **462** is substantially free of donor-type impurity atoms.

FIG. **6** shows a graph that illustrates the dopant profile of an NMOS I/O well below an overlying gate structure in accordance with the present invention. As shown in FIG. **6**, line F1 illustrates the concentration of acceptor-type impurity atoms under gate **434** in NMOS I/O well **424**. (Alternately, line F1 illustrates the concentration of acceptor-type impurity atoms under gate **237** in NMOS I/O well **224**.) Further, as shown in the graph, there are no donor-type impurity atoms under gate **434** in NMOS I/O well **424** (or under gate **237** in NMOS I/O well **224**). By comparison, as also shown in FIG. **6**, line F2 illustrates the concentration of acceptor-type impurity atoms, while line F3 represents the concentration of donor-type impurity atoms under the gate of an NMOS I/O well which has been counter doped as in one of the prior art approaches.

P-type well **422**, p-type channel region **440**, p-type below-the-channel region **441**, p-type halo **443**, p-type halo **444**, n-type source **437/481**, n-type drain **438/482**, gate dielectric structure **427**, gate structure **432**, and sidewall spacer **475** define a core NMOS transistor **490**, which can be used to implement NMOS transistor **133**.

Further, n-type well **418**, n-type channel region **450**, n-type below-the-channel region **451**, n-type halo **453**, n-type halo **454**, p-type source **446/486**, p-type drain **447/487**, gate dielectric structure **428**, gate structure **433**, and sidewall spacer **476** define a core PMOS transistor **491**, which can be used to implement PMOS transistor **172**.

In addition, p-type well **224**, p-type channel region **460**, p-type below-the-channel region **461**, p-type halo **463**, p-type halo **464**, n-type source **457/483**, n-type drain **458/484**, gate dielectric structure **425**, gate structure **434**, and sidewall spacer **477** define an I/O NMOS transistor **492**, which can be used to implement NMOS transistor **340**.

Further, n-type well **420**, n-type channel region **470**, n-type below-the-channel region **471**, n-type halo **473**, n-type halo **474**, p-type source **466/488**, p-type drain **467/489**, gate dielectric structure **426**, gate structure **435**, and sidewall spacer **478** define an I/O PMOS transistor **493**, which can be used to implement PMOS transistor **380**. The transistors **490**, **491**, **492**, and **493**, in turn, form a dual gate dielectric CMOS structure **495**.

It should be understood that the above descriptions are examples of the present invention, and that various alternatives of the invention described herein may be employed in practicing the invention. Thus, it is intended that the following claims define the scope of the invention and that structures and methods within the scope of these claims and their equivalents be covered thereby.

What is claimed is:

1. A semiconductor structure comprising:

a semiconductor region;

a first body region that touches the semiconductor region, the first body region having a first channel region and a below-the-first channel region that touches and lies below the first channel region, the first channel region having a first middle point, the first channel region at the first middle point including a first type of impurity atoms, being substantially free of a second type of impurity atoms, and having an average dopant concentration, the below-the-first channel region having a dopant profile;

a first source region that touches the first body region, the first source region including substantially more of the second type of impurity atoms than the first type of impurity atoms;

a first drain region that touches the first body region, the first drain region being spaced apart from the first source region, and including substantially more of the second type of impurity atoms than the first type of impurity atoms, the first middle point lying mid-way between the first source and drain regions;

a second body region that touches the semiconductor region and lies spaced apart from the first body region, the second body region having a second channel region and a below-the-second channel region that touches and lies below the second channel region, the second channel region having a second middle point, the second channel region at the second middle point including the first type of impurity atoms, being substantially free of the second type of impurity atoms, and having an average dopant concentration that is less than the average dopant concentration of the first channel region at the first middle point, the below-the-second channel region having a dopant profile that is substantially identical to the dopant profile of the below-the-first channel region;

a second source region that touches the second body region, the second source region including substantially more of the second type of impurity atoms than the first type of impurity atoms; and

a second drain region that touches the second body region, the second drain region being spaced apart from the second source region and including substantially more of the second type of impurity atoms than the first type of impurity atoms, the second middle point lying mid-way between the second source and second drain regions.

2. The semiconductor structure of claim 1 and further comprising:

a thin gate dielectric structure that touches and lies above the first channel region; and

a first gate that touches the thin gate dielectric structure and lies above the first channel region and the thin gate dielectric structure.

3. The semiconductor structure of claim 2 and further comprising:

a thick gate dielectric structure that touches and lies above the second channel region; and

a second gate that touches the thick gate dielectric structure and lies above the second channel region and the thick gate dielectric structure.

4. The semiconductor structure of claim 3 wherein the first channel region has a first length and the second channel region has a second length that is substantially longer than the first length.

5. The semiconductor structure of claim 3 wherein:

the first source region includes a first source extension region and a first main source region; and

the second source region includes a second source extension region and a second main source region, the first source extension region and the second source extension region having substantially equal depths.

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